FTTx PON
Technology and Testing

A detailed review of system performances, issues and testing solutions.

Andre Girard, Ph.D.,
EXFO Electro-Optical Engineering Inc.

FTTx Test Solutions

EXFO
EXPERTISE REACHING OUT

André Girard, Ph.D., Senior Member of Technical Staff

EXFO Electro-Optical Engineering

Dr. Girard is Convenor of the IEC Working Group (WG) 7 on Passive Components. WG 7 falls under Subcommittee SC-86B on Fibre Optic Interconnecting Devices and Passive Components which, in turn, comes under Technical Committee (TC)- 86 on Fibre Optics[1]. The main objective of WG 7 is developing performance standards and specifications for fiber-optic passive components such as WDM devices, attenuators, isolators, branching devices and switches.

In addition, Dr. Girard is a delegate at the IEC TC 86 with active participation in SC 86B on Passive Components (task leader on PMD and ITU liaison officer) and SC 86C on Optical Fibre, Active Devices and Systems (Chairman of the Canadian SC 86C National Committee). As well, he is the task leader on general information documentation on PMD.

Dr. Girard is also a member of the TIA and Secretary of TIA FO-4.3 Subcommittee on Fiber-Optic Interconnecting Devices of Technical Committee FO-4 on Fiber Optics[2].

Finally, Dr. Girard is a delegate at the ITU-T, Study Group (SG) 15, on Optical and Other Transport Networks. Within SG 15, he is the Editor of Recommendations G.671 on Transmission Characteristics of Optical Components and Subsystems, G.661 on Definitions and Test Methods for the Relevant Generic Parameters of Optical Amplifier Devices and Subsystems, and G.662 on Generic Characteristics of Optical Amplifier Devices and Subsystems.

Dr. Girard holds a Ph.D. and M.Sc. in lasers from the Quebec National Scientific Research Institute and a B.Sc. in physics from Laval University in Canada. He has over 30 years of experience and expertise in optics.

[1]*ITU and IEC use UK English*

[2]*TIA uses US English*

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Andre Girard

PREFACE

Since the publication of EXFO's first book (Guide to WDM Technology and Testing) in 2000, there has been a tremendous amount of progress in the global telecommunications industry, and in fiber-optic telecommunications in particular. Many of the related terms or buzzwords, such as broadband, very high bit rate and access are now quite common.

EXFO, too, has evolved during this period, and the company has published several guides and application notes covering different aspects of our field (these documents can be found and/or ordered at www.exfo.com). Although we are still very focused on our original mission of being a leader in telecom testing equipment, it is the expertise behind the instruments and our collaboration with customers that are at the heart of our company values. EXFO's slogan, *Expertise Reaching Out,* appropriately reflects our ongoing commitment to the industry and is representative of the spirit in which this book was written.

The timing of the publication is also of great importance, as this is the moment when telecom professionals are showing an increasing interest in learning more about this progressive area; i.e., the development and deployment of fiber-to-the-home (FTTH) using passive optical networks (PONs).

Indeed, FTTx and PON are some of today's most popular buzzwords, and just as a new wine matures, this book is a more seasoned follow-up to EXFO's pocket-sized FTTx PON Guide: Testing Passive Optical Networks, first published for the industry in February 2004.

The present work is more extensive than our pocket guide and further introduces telecom managers, engineers, technicians, professors and students to the fascinating world of passive networking technology. *FTTx PON Technology and Testing* presents a detailed description of PON architecture, its basic system configurations, topologies, components, and performance characteristics, both at the physical layer and at the protocol transport layer. The book also contains several accompanying illustrations and tables to support the text and thus facilitate assimilation.

Other topics covered include the equipment located at the central office and at the subscribers' premises; the various outside plant components and their installation; as well as the development of the new set of international standards that such a technology requires. Finally, the book proposes an in-depth study of the related test procedures for PON installation service activation, operation and maintenance, some of which will be unfamiliar and very challenging for installers and operators of PONs.

We hope that this book will provide you with a deeper understanding of passive optical networking technology, which, in the near future, may again change our way of life as high-speed and WDM networks have changed the way we use our computers and the Internet.

EXFO is a Platinum Member of the FTTH Council

FTTH council | fiber to the home

Chapter 1

Introduction

INTRODUCTION

Since the development of optical fiber, fiber-optic telecommunications, the personal computer (PC) and the Internet, our lives have been dominated by bandwidth consumption. Although many of us do not realize it, daily activities that are now considered trivial consume a significant amount of bandwidth.

The most demanding of these applications is the use of video, especially high-definition television (HDTV), followed by standard-definition television (SDTV). The table below gives an overview of how much bandwidth is required for some of today's most common applications.

Table 1.1 – Bandwidth consumption for typical service applications

<table>
<tr><th rowspan="3">Applications</th><th colspan="3">Bandwidth (Mb/s)</th></tr>
<tr><th rowspan="2">Single application</th><th colspan="2">Maximum</th></tr>
<tr><th>MPEG-2</th><th>MPEG-4/WM 9</th></tr>
<tr><td>Voice (per channel)</td><td>0.064</td><td colspan="2">0.5 (Multi-lines)</td></tr>
<tr><td>Web Browsing</td><td>1 – 2</td><td colspan="2" rowspan="2">5 (2 PC's)</td></tr>
<tr><td>6 Mpixel JPEG Picture in 10s*</td><td>2</td></tr>
<tr><td>SDTV (MPEG-2)</td><td>4 – 6**</td><td>10 (2 TV sets)</td><td></td></tr>
<tr><td>SDTV (MPEG-4)</td><td>2</td><td></td><td>5 (2 TV sets)</td></tr>
<tr><td>HDTV (MPEG-2)</td><td>20</td><td>20 (1 TV set)</td><td></td></tr>
<tr><td>HDTV (MPEG-4)</td><td>9</td><td rowspan="2"></td><td rowspan="2">8-10 (1 TV set)</td></tr>
<tr><td>HDTV (Windows Media 9 - WM 9)</td><td>8</td></tr>
<tr><td>Total-32 premises***</td><td></td><td>~35/1120</td><td>~20/640</td></tr>
</table>

* Realtime = 50 Mb/s min.

** 300 - 400 digital video programs

*** Not including video phone or realtime interactive gaming, etc.
MPEG: motion picture experts group (www.mpeg.org)
JPEG: joint photographic experts group (www.jpeg.org)

It must be noted, however, that total bandwidth consumption is distributed differently, depending on the part of the world, since the quantity and frequency of use of these applications vary from country to country.

1.1 Current Bandwidth Usage Worldwide

The variation in bandwidth consumption depends on many factors, such as culture, climate, local infrastructure, and even physical space or distance. For example, in colder climates, people stay indoors more, which favors activities like watching television and Web browsing. In contrast, some cultures value a deep connection to nature or to other people, which in this case encourages people to go out instead of watching TV or working on the computer. While more extroverted cultures may use more phone services than video services, countries with significant populations scattered outside urban centers may have more cellular phone users than land lines.

For the sole purpose of describing the trends that are occurring in different parts of the world, bandwidth users may be classified into three main categories, according to their geographical areas and service use.

For instance, in the US and Canada, technology, productivity and convenience has played a major role in society since the industrial revolution. Today, in this part of the world, television remains the biggest and most popular vehicle of culture, perhaps more so than anywhere else. In some areas, the colder climate has further reinforced the trend, inciting people to stay indoors and do more things at home. For example, over the past 15 years, computers and the Internet have increasingly become an integral part of the average American and Canadian's daily life; not only at work or at school, but also at home, be it for business or leisure. In terms of geography, most families live outside urban areas, which typically means long commutes to work every day. This growing phenomenon, along with the now common computer requirements in schools, has encouraged many people to have home offices to save time and facilitate schoolwork and business. Of course, many people simply enjoy surfing the Web or playing computer games just for fun as well. All this translates into extensive bandwidth demand for services to the home, so we can call them *Telhomers.*

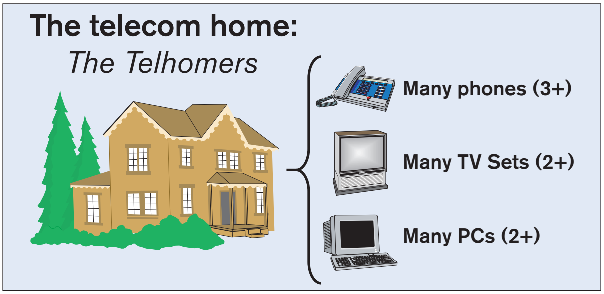


Figure 1.1 – The American model for consumption of broadband telecom services

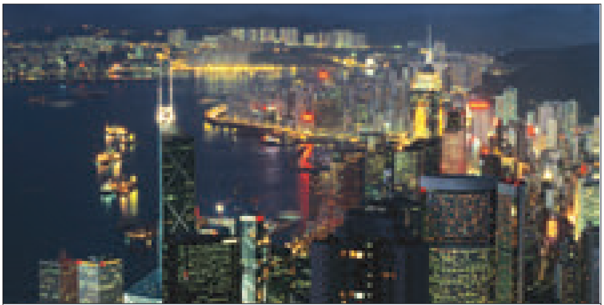
Figure 1-1 illustrates the typical connections and uses of the common upper-middle-class home in the US and Canada. These houses have many phones and more than one TV; typically, one per floor (some homes may also have one or more HDTV sets). Several PCs are also common; often, there is one for the parents, one for the children and possibly one more if there is an office in the house (known as small office home office or SOHO, which usually includes a separate phone line, independent from that of the residential family line).

In contrast, while Asia, too, consists of industrialized societies in which technology and productivity play a major role, most Asian countries also have significant rural populations that do not have access to television. They do, however, have access to telephone services (especially cellular phones) and the Internet, which contributes to bandwidth consumption even in remote locations.

In urban areas, the dense populations and lack of physical space have led to the construction of mega apartment buildings, which although may limit the per-capita use of bandwidth (compared to the multiple connections in a North American home, for example), it certainly does not limit the frequency and quantity of use. In fact, in China alone, there are more than 100 million Internet subscribers. For this reason, we can call this group the *Telenese.*

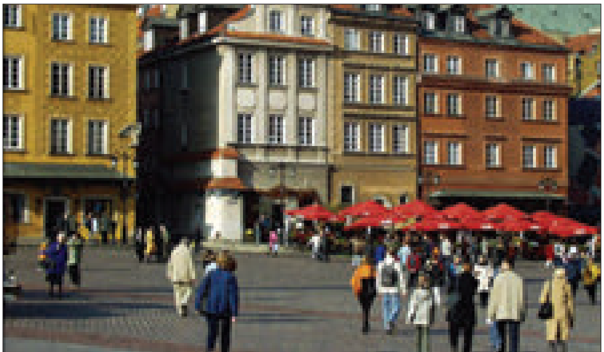
Figure 1-2 illustrates a common type of apartment complex in Asia, which houses hundreds, sometimes thousands of people, most of whom have Internet connections and phone services.

In Europe, the situation is somehow a little different. Although the usual services such as telephone, Internet and television are deployed massively, in some countries, the high cost of residential telephone lines and scattered populations in remote areas have caused the number of cellular phone users to surpass the number of land lines.



China = 100,000,000 Internet Subscribers: The Telenese

Figure 1.2 – The Asian model for consumption of broadband telecom services



The Cafeneans

Figure 1.3 – The European model for consumption of broadband telecom services

Internet connections are also a big portion of the European bandwidth consumption, whereas television services, on the other hand, are used much less frequently than they are in America, for instance. Culturally, many European societies prefer going out and getting together to staying in and watching television. They often meet in cafes for casual conversation or gather in large groups to watch football (soccer) games. For these reasons, we can call European bandwidth users *Cafeneans*. Figure 1-3 illustrates a busy European cafe.

The above is, of course, but a brief and simplified overview of service usage over three continents. Nonetheless, it provides a general backdrop for the following sections, allowing the reader to better understand the context of the information provided.

1.2 Network Technologies

In order to support the service applications enumerated in Table 1-1 above, a number of network technologies are proposed, each with advantages and drawbacks. Table 1-2 lists available transport solutions (such as copper or optical fiber) for supporting the applications in the access market. Before going any further, it must be noted that the actual "transporting" is done by what is known as bandwidth, which refers not only to the quantity of data it can carry, but also to the speed at which the signals travel; bandwidth is measured in megabits or gigabits per second (abbreviated Mb/s, Mbps or Mbit/s, and Gb/s, Gbps or Gbit/s, respectively; Mb/s and Gb/s will be used herein).

One way of appreciating the efficiency of broadband access technologies is to illustrate, for each architecture, the product of the bandwidth's speed and the reach of the signal it carries. This is measured in Mb/s x km. Figure 1.4 shows the speed at which current technologies run.

Table 1.2 – Development of broadband access transport technologies

Transport			FTTC									FTTH		
			ADSL				VDSL					PON		
			Basic	+	2	2+	Basic			2		BPON	GPON	EPON
Bandwidth (Mb/s)	Max	Down[1]	3	8	15	20	13	26	52	30	100	155.52 622.08 1244.16	1244.16 2488.32	1000 nominal
	Shared	1x16												~80
		1x32										~20 at 622 ~40 at 1244.16	~40 at 1244.16 ~80 at 24488.32	~40
Max. Reach (km)			3	3	6	1.5	1.5	1	0.3	1	0.3	20		10 20[2]

Limit for SDTV

Limit for HDTV

No bandwidth limit but distance-limited

[1]Upstream: 1) 1.6 - 2.3 Mb/s
(3 types) 2) 19.2 Mb/s
3) Symmetric

[2]With FEC

AADSL: Asymmetric digital subscriber line
BPON: Broadband PON
EPON: Ethernet-based PON
FEC: Forward error correction
FTTC: Fiber-to-the-curb (refers to the use of fiber-optic cable directly to the curbs near homes or businesses and copper media between the curb and the user network)
FTTH: Fiber-to-the-home
GPON: Gigabit-capable PON
PON: Passive optical network
VDSL: Very-high-speed digital subscriber line

The development of the singlemode optical fiber, with its almost unlimited bandwidth, opened the door to massive deployment of long-haul and metropolitan point-to-point (P2P)[1] fiber-optic networks. The use of fiber-optic cable, rather than copper cable, resulted in three important changes:

- Massive capacity increase
- Significant cost reductions (equipment, operation and maintenance)
- Greatly improved quality of service (QoS)

Figure 1.5 illustrates examples of typical network structures, while Figure 1.6 presents examples of fiber-optic P2P networks and shows some of the techniques that have been used to increase their capacity. Originally, a single channel was carried over each optical fiber using a single wavelength. Since no amplification was used, the length of each optical link was limited to approximately 100 km with sufficient optical power. The advent of wavelength-division multiplexing (WDM) made it possible to carry many channels (each using a different wavelength) over a single fiber, without cross-interference. Dense wavelength-division multiplexing (DWDM) further increased this capacity, allowing even more wavelength channels.

[1] A point-to-point (P2P) network is a dedicated communication link operating over a fiber pair; one for downstream transmission, the other for upstream transmission. (This should not be confused with "peer-to-peer" file-sharing networks, also abbreviated as P2P.)

In addition, the use of erbium-doped fiber amplifiers (EDFAs), which amplify optical signals directly, without optical-electrical-optical conversion, allowed for the construction of long-haul P2P networks with few or no electronic components.

Metropolitan-area networks (MANs) are also fiber-based and make use of lower-cost coarse wavelength-division multiplexing (CWDM) to transmit multiple channels (typically 18 over low-water-peak fiber) per fiber over relatively short P2P links.

Although most access networks serving small businesses and residential customers are still copper-based, subscribers in a few countries around the world have a P2P fiber-optic connection to a central office (CO). As shown in Figure 1.6(c), this requires a dedicated optical line terminal (OLT) at the CO, as well as a pair of optical fibers for each subscriber where an optical network unit (ONU[2]) is connected to the fiber pair.

In spite of its advantages, optical fiber has not been widely used in the "last mile" (i.e., the segment of the network that extends from the CO directly to the subscriber). Because of the high cost and limited availability of optical access services, this segment is typically copper-based (as shown in Figure 1.7), and the high-speed services available to residential clients and small businesses are limited to generic digital subscriber lines (xDSL) and hybrid fiber coax (HFC).

The main alternative to fiber optics — wireless transmission with direct broadcast service (DBS) — requires an antenna and a receiver (as shown in Figure 1-5). Therefore, current services present the following shortcomings:

- They provide limited bandwidth in a context where there is an explosive growth in demand for more bandwidth, higher-speed services and longer reach.
- They use different media and transmission equipment requiring multiple installations and extensive maintenance.
- They allow carriers to provide triple-play (voice, video and data) services and other high-speed interactive applications to residential customers, but they require considerable compression techniques. Copper networks have a shorter reach, increasing the life-cycle cost substantially.

Although fiber optics overcomes most of these limitations, one of the obstacles to providing fiber-optic services directly to residences and small businesses, including small offices and home offices (SOHOs), has been the high cost of connecting each subscriber to the CO (i.e., the cost of deploying the fiber cable). A high number of point-to-point (P2P) connections would require many active components and a high-fiber-count cable, thus leading to prohibitive installation and maintenance costs, compared to a traditional copper distribution network (which is getting very old and requires maintenance). Figure 1.8 shows different optical fiber connections used in the access network.

While also supporting P2P architecture, fiber-to-the-home (FTTH), also called fiber-to-the-premises (FTTP), provides a point-to-multipoint (P2MP[3]) connection that offers an attractive solution to these problems. With FTTH P2MP PONs, there

[2] The ONU is called optical network terminal when it is connected to the user network interface

[3] A point-to-multipoint network provides a link from one upstream terminal to multiple downstream terminals.

are no active components between the CO and each subscriber, allowing several subscribers to share the same connection. This is accomplished by using one or more passive splitters to connect, in some cases, up to 32 subscribers to the same feeder fiber. This P2MP architecture dramatically reduces the network installation, management, and maintenance costs.

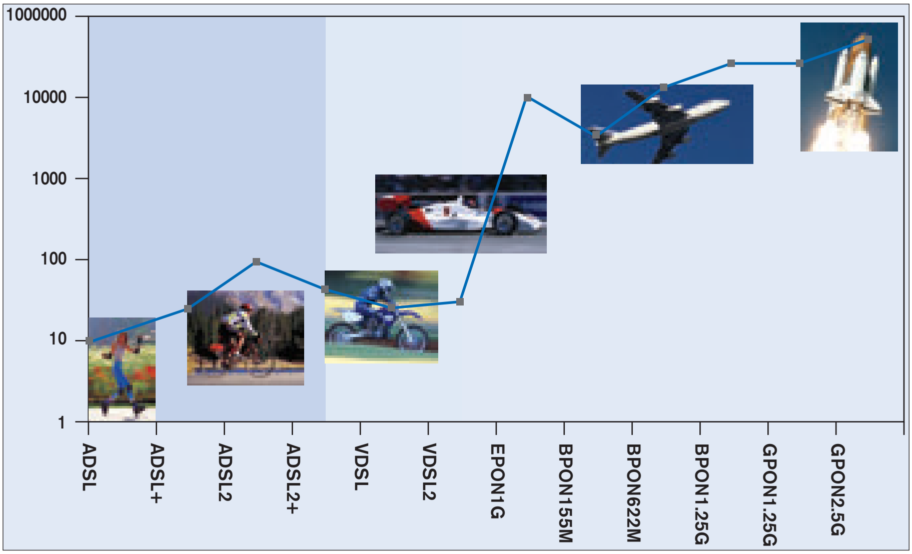


Figure 1.4 – Assessment of the efficiency of various access network technologies

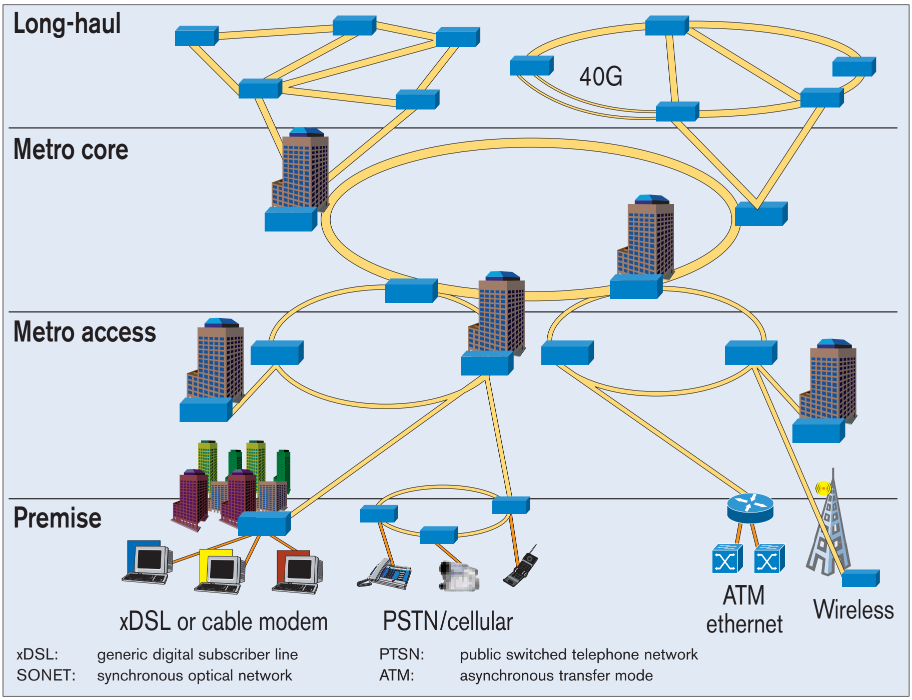


Figure 1.5 – Terrestrial fiber-optic networks

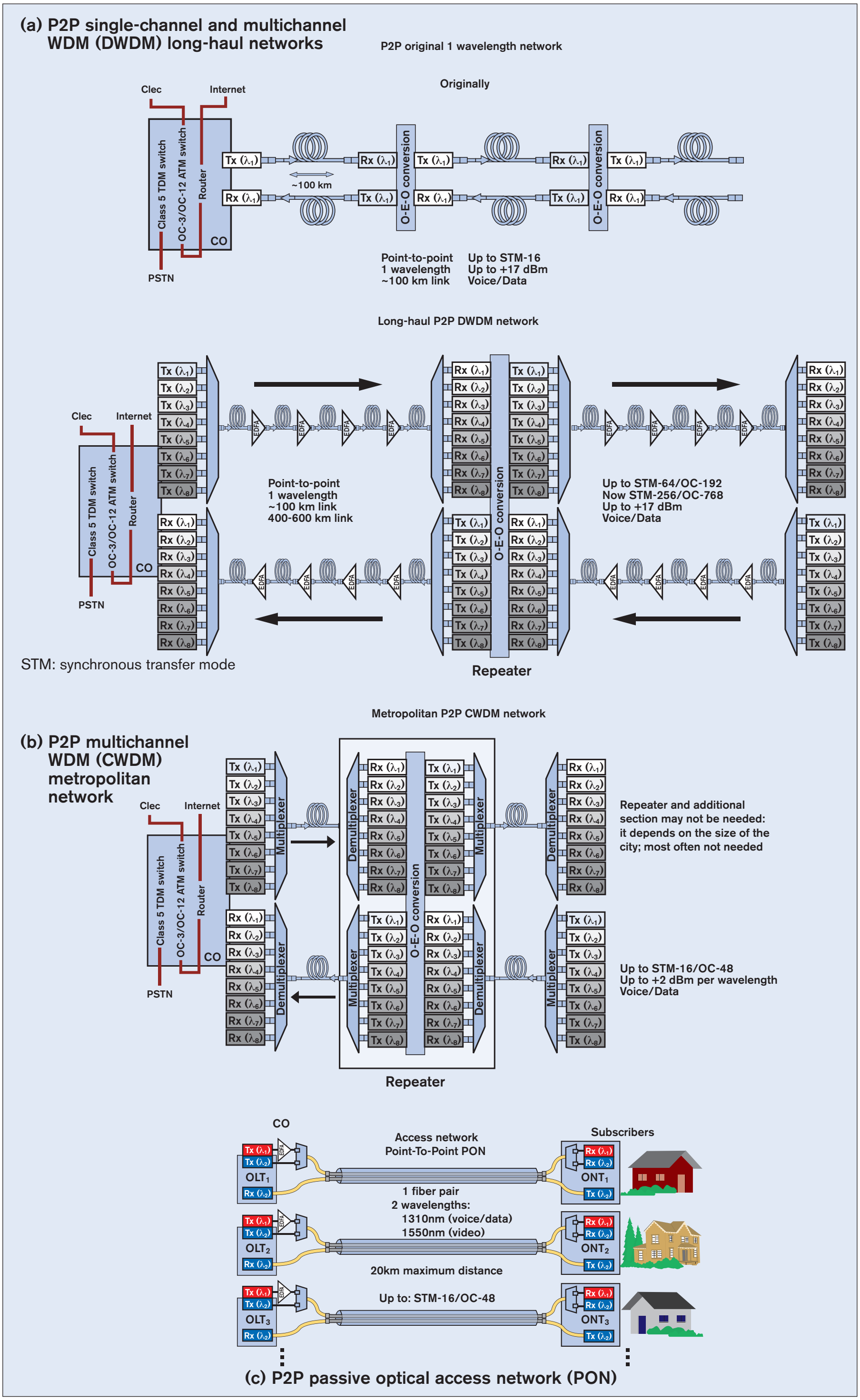


Figure 1.6 – Examples of point-to-point (P2P) optical networks

Figure 1.9 shows examples of a P2MP PON. In this figure, each OLT at the CO is connected through a single feeder fiber to a splitter, which is in turn connected to all subscribers sharing the available bandwidth. Each subscriber has a connection to a single fiber, and different wavelengths are used on this fiber for upstream and downstream transmission of voice and data, as well as downstream video transmission[4].

The difference between P2P and P2MP networks is summarized in Table 1.3.

Table 1.3 – Differences between P2P and P2MP PON

Parameter	P2P	P2MP
Traffic direction/fiber	One way	Both ways
Number of fibers/subscriber	Two	One
Bandwidth access	Direct	Shared
Low-cost available equipment	Established	To be proven
Maintenance	More	Less
Active components	More	Fewer
Passive components	Fewer	More
Laser power	Lower	Higher
Cost Limitation	Fiber	Passive Components
	Active Components	ONU
	Maintenance	

Tx: transmitter Rx: receiver OSP: outside plant

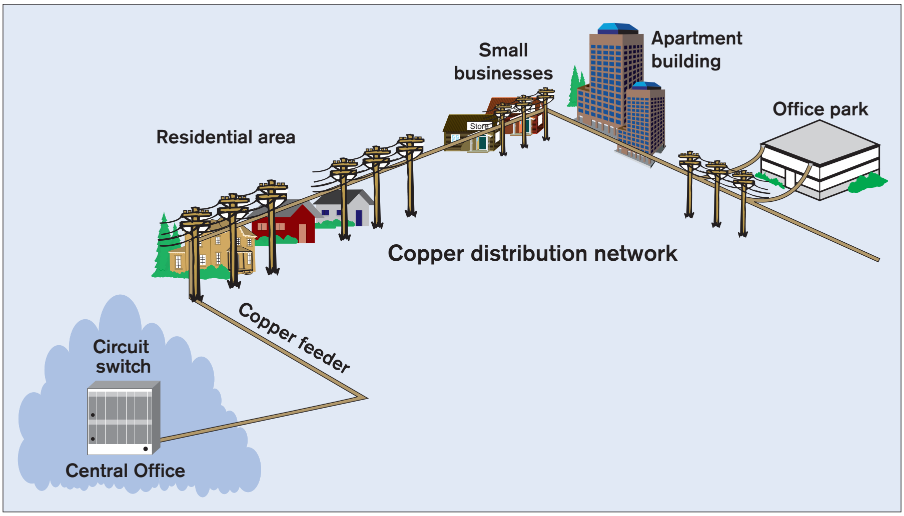


Figure 1.7 – Traditional copper-based access network

[4] *In some PONs, where sufficient fiber has already been laid, broadcast video may be carried by a dedicated fiber. In this case, each subscriber would be connected using two fibers.*

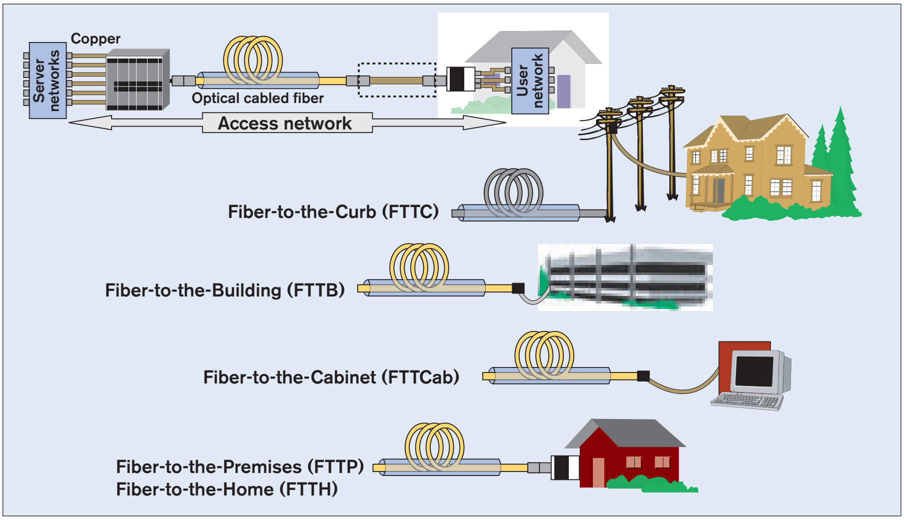


Figure 1.8 – Variations of the access network architecture

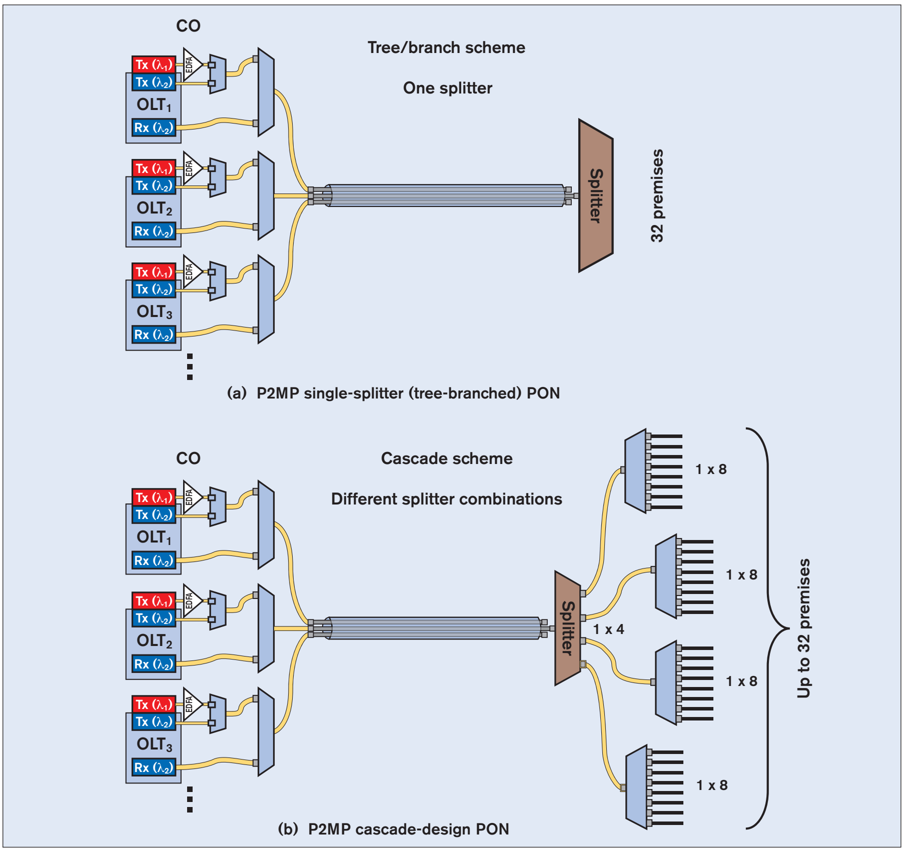


Figure 1.9 – Examples of point-to-multipoint (P2MP) networks

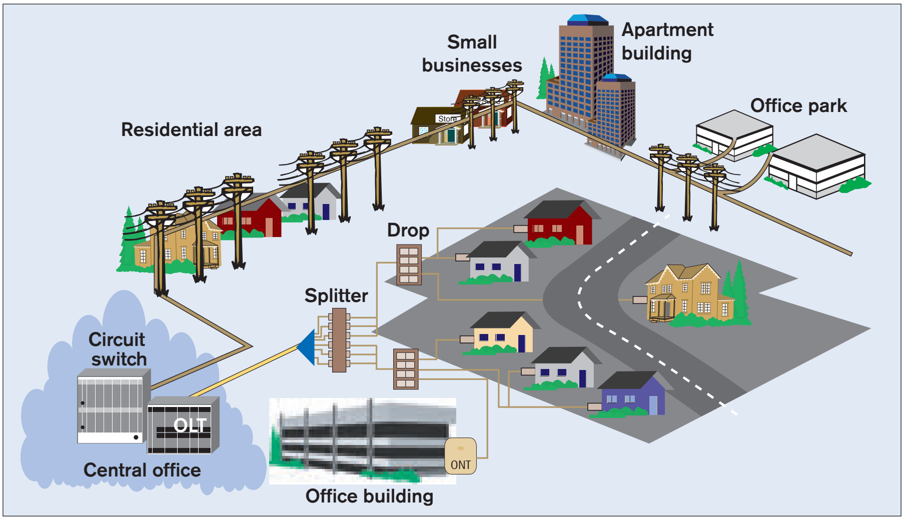


Figure 1.10 – Example of FTTH PON in new housing (Greenfield) development

1.3 Historical Development of FTTH

In the mid 90s, a group of international network service providers gathered to develop standards documents that would eventually define the new fiber-to-the-home passive optical network. It would allow them to offer cost-effective connections to subscribers, open a new market, and help incumbent service providers to better compete in their market by developing standardized equipment. The group created the full-service access network (FSAN)[5]. Furthermore, the US legislature signed the Telecommunications Act of 1996 to "promote and reduce regulation in order to secure lower prices and higher-quality services for American telecommunications consumers and encourage the rapid deployment of new telecommunications technology." This policy as been followed by many other countries around the world.

The International Telecommunication Union's telecommunications standardization sector (ITU-T)[6] turned FSAN specifications into recommendations. The FSAN specification for asynchronous transfer mode (ATM)[7]-based PONs became ITU-T Recommendation G.983.1 in 1998 [see PON-related ITU-T recommendations in Bibliography].

In 2001, the FTTH Council was formed to promote FTTH in North America and to advise the US legislature. This resulted in the Broadband Internet Access Act of 2001, which provides tax incentives to companies that invest in next-generation broadband equipment. The term broadband denotes an access bandwidth to the user comparable to xDSL and above; i.e., a few Mb/s and higher. It is expected that the capacity required by new applications may increase to 1 Gb/s by 2015.

[5] *www.fsanweb.org*
[6] *www.itu.int*
[7] *ATM is a network technology based on transferring data in cells of a fixed size.*

In 2003, the US Federal Communication Commission (FCC) removed unbundling requirements on FTTH networks, freeing regional Bell operating companies (RBOCs) from their obligation to allow competitive local-exchange carriers (CLECs) to use their network infrastructures, and thus making the technology more attractive to major carriers. This means that RBOCs can now invest in last-mile fiber infrastructure without having to share it with competitors, which should provide a major incentive towards the deployment of FTTH networks. Some predict a US$1 billion market for FTTH networks for RBOCs alone.

Table 1.4 summarizes the evolution of international standards (also refer to the bibliography section, which lists many PON standards as well as the date that each standard was released).

Table 1.4 – Timeline for the development of PON

Time Period	Event	Comments
1995	FSAN initiative	▪ Seven international network operators (Bellsouth, British Telecom, Deutsch Telekom, France Telecom, GTE, NTT, Telecom Italia) join together ▪ First formal PON activity ▪ Goal: common equipment standards
1998 IT	FSAN system specification = U-T Recommendation G.983.1 Broadband optical access systems based on Passive Optical Networks (PON)	▪ First PON international standard to be followed by many more
	Deployment initiated in Asia (mainly Japan and Korea) and in Europe (mainly Sweden and more to follow)	
1999	Ethernet PON (EPON) emerges in the Institute of Electrical and Electronic Engineers (IEEE)	
2000	IEEE 802.3 Ethernet Working Group creates the 802.3ah Ethernet in the First Mile (EFM) task force	
2001	ITU-T Study Group 15 Working Party 1 Question 2 initiates work on Gigabit PON (GPON)	
	US Broadband Internet Access Act	▪ Tax incentives for investment in next-generation broadband equipment
2003	US FCC removes unbundling requirements	▪ RBOCs not forced anymore to allow CLECs using their new networks infrastructures ▪ Major incentive towards PON deployment ▪ RBOCs to invest in new last-mile FO infrastructures ▪ Verizon/SBC/Bellsouth publishing a Request For Proposals (RFP) on PON deployment
	ITU-T publishes Recommendation G.984.1	▪ First GPON standard
2004	IEEE publishers IEEE 802.3ah standards	▪ First EPON standard
	Start of a huge FTTH PON deployment in the USA	
2005	Issues regarding video franchising in PON All public Telegraph and Telephone (PTTs) companies of the western world start to look into FTTH PON	

As a result of all these recent developments, interest in FTTH has spurred exponentially:

- SOHOs are demanding more bandwidth and more services.
- FTTH PON offers the high-bandwidth capability of optical fibers and a wide diversity of services (data, voice, and video) at a low cost because a number of end users can share bandwidth on a single fiber, and because all outside plant equipment is passive.
- New standards such as those established by the ITU-T and the Institute of Electronic and Electrical Engineers (IEEE)[8] have greatly increased the design commonality, capacity, survivability, security and versatility of PONs, opening the opportunity for mass economy of scale and tremendously lower costs that were not conceivable before.

FTTH PON can now be offered by many different types of carriers:

- Incumbent local exchange carriers (ILECs) and RBOCs
- Rural local exchange carriers (RLECs)
- CLECs
- Utility companies
- Municipalities, etc.
- FTTH PONs are increasingly installed in new housing (Greenfield) developments (see Figure 1.10)

In addition, many countries in Asia (China, Japan, Korea, Singapore and Taiwan) and Europe are presently testing or deploying PONs, and the IEEE-802.3ah [see IEEE access network standards in Bibliography] task force[9] has currently drafted standards an for Ethernet-based PON (EPON). From a worldwide market perspective, PON revenues surged 240% from 2002 to 2003 to US$ 182 million.

Table 1.5 describes a number of available services typically supported by FTTH PONs. Voice communication over the PON can be provided using conventional switched circuits or voice-over-Internet protocol (VoIP). Similarly, video can be provided using radio-frequency (RF) cable-TV broadcast standards or IPTV (digital TV transmitted using the Internet protocol; the expression video-over-IP is also used).

[8] *www.ieee.org*
[9] *grouper.ieee.org/groups/802/3/efm*

Table 1.5 – Available PON services

Data	Voice	Video
▪ High-Speed Internet ▪ Legacy Data to Corporate Customers ▪ Private Lines ▪ Frame Relay ▪ ATM Connections ▪ Interactive Gaming ▪ Monitoring and Security Systems ▪ Future Services	Switched circuits or voice over IP (VoIP) Single or Multiple Phone Lines	▪ Digital and Analog Broadcast ▪ Video or Internet protocol TV (IPTV) ▪ High-Definition Television (HDTV) ▪ Video-on-Demand (VOD) ▪ Interactive TV/Pay Per View ▪ Real-time video phone/video conference

As shown in Table 1-5, there are a lot of telecommunication applications available over access networks. However, experts believe that an application requiring as much bandwidth upstream as downstream, called the “killer application” in FTTH jargon, has yet to surface.

Chapter 2

FTTH PON Architectures and Topology

Different architectures exist for connecting subscribers to a PON. However, each PON requires at least the following (see Figure 2.1):

- An optical line terminal (OLT) at the CO in P2MP and P2P PONs
- Video distribution equipment also at the CO
- A feeder fiber from the CO to a splitter in P2MP PONs (the fiber is part of a multifiber cable; one splitter per fiber); a fiber pair for P2P PONs
- One splitter per feeder fiber; PONs can use multiple splitters in a cascade or tree design topology (see Figure 1.9)
- Distribution fibers and drop cables between the splitter branches and the optical network terminals (ONTs) (one distribution fiber/drop cable per ONT); the same feeder fiber (pair) in P2P PONs
- An ONT (ONU connected to the UNI) located at each subscriber's premises in P2MP and P2P PONs

The feeder, splitter(s), distribution cables and drop cables form the optical distribution network (ODN) of the P2MP PON. Since one PON typically provides service to up to 32 subscribers (BPON), many such networks, each originating from the same CO, are usually required to serve a community.

The OLT at the CO is interfaced with the public switched telephone network (PSTN) and the Internet (see Figure 2.1). Video signals enter the system from the cable television (CATV) head-end or from a DBS satellite feed. The video sources can be converted to optical format by an optical video transmitter,

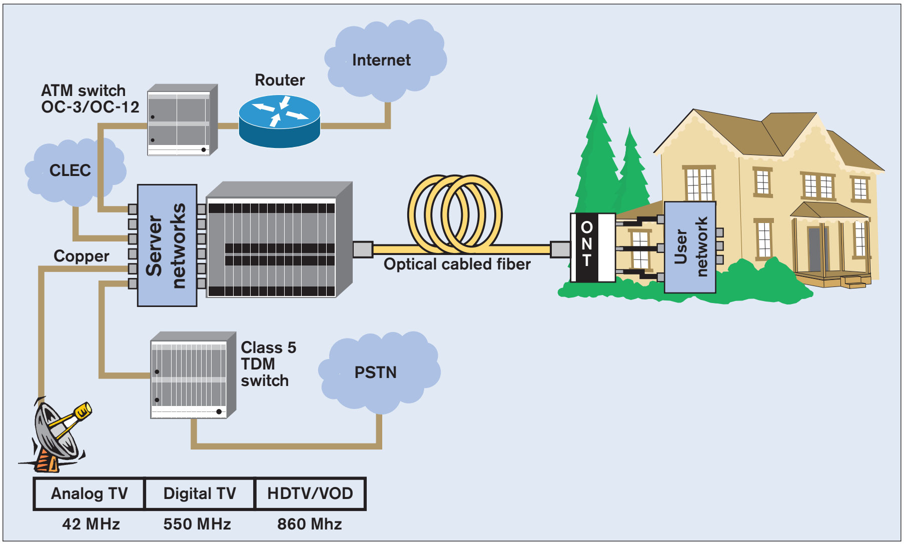


Figure 2.1 – FTTH PON basic system architecture

[10] The US Federal Communications Commission has ruled that all large TVs must be digital-ready by July 1, 2005; all TVs with 25" to 36" screens must be ready by March 1, 2006. In addition, Congress is considering proposals to set a deadline for ending the broadcast of analog television signals in the US and only using digital broadcast. These measures will favor the use of IPTV rather than video overly in PONs.

amplified and coupled through a wide wavelength-division multiplexing (WWDM) coupler (not shown in Figure 2.1) to the optical signal from the OLT. Alternatively, the video signals can be interfaced with the OLT in digital form for IPTV[10] or in analog form for overlay. These signals are transmitted downstream along the same optical fiber. Voice and data can be transmitted upstream from the ONTs[11]. Figure 2.2 shows examples of OLTs and Figure 2.3 shows an example of terminal equipment at the CO.

Courtesy of Optical Solutions Inc.

Figure 2.2 – Examples of OLTs in terminal equipment

Courtesy of Telecom Services Corporation (TSC) – St-Marys, OH USA

Figure 2.3 – Example of FTTH PON equipment at the CO

[11] *With digital IPTV, the signal may be transmitted on the same wavelength as the data or voice if VoIP is used. In this case, video may also be transmitted upstream, creating an opening for new services and applications.*

The feeder fiber from the CO is brought to a fiber distribution hub (FDH), where one or more splitters are located; typically, near a group of customers (a km or so). From that point, one or more passive splitters (depending on the splitter topology) are used to connect customers. Each customer premises is provided with an ONT (see Figure 2.4) connected to one splitter branch. The ONT provides connections for the different services (voice, Ethernet, and video).

Courtesy of Optical Solutions

Figure 2.4 – Example of FTTH PON ONT

Figure 2.5 illustrates the P2MP PON wavelength allocation based on ITU-T Recommendation G.983.3 (BPON). The OLT provides voice and data downstream transmission using a 1490 nm wavelength band, while the ONT provides voice and data upstream transmission on a 1310 nm wavelength band. Analog video overlay is also possible using the 1550 nm band. This use of wide wavelength-division multiplexing (WWDM) allows non-interfering bidirectional transmission over the same fiber.

Figure 2.6 shows the types of lasers used for upstream and downstream transmission. A cooled directly modulated, narrow-spectrum distributed-feedback (DFB) laser is used for downstream voice and data transmission from the CO, whereas a low-cost uncooled directly modulated multifrequency Fabry-Perot (FP) laser is used in the ONTs for upstream voice and data transmission. The analog overlaid video is transported by a cooled externally modulated DFB laser.

The figure also shows the ITU-T bands with corresponding names and wavelength ranges, as well as the bands enabling different transmission types (CWDM, DWDM, WWDM PON).

ITU-T Recommendation G.983.3 specifies the use of additional wavelength bands, such as the “enhancement band”; for a video distribution service (VDS), the enhancement band covers 1550 to 1560 nm. For additional digital services (ADS), it covers 1539 to 1565 nm.

When the enhancement band is used to provide downstream video overlay on a 1550 nm wavelength, the VDS must be amplified at the CO using an erbium-doped fiber amplifier (EDFA). This signal is amplified to high power, typically +21 to +23 dBm, and is then coupled to the data/voice signal using a WWDM coupler. The coupler classification is based on IEC 62074-1 (see List of IEC Standards section) and ITU-T Recommendation G.671. However, if IPTV is used for video, or if no video is transmitted, the EDFA and the WWDM coupler are not required. In this case, a lower power signal on a single wavelength (1490 nm) is used for all downstream transmission, while 1310 nm is used for upstream voice and data transmission. A bidirectional WWDM coupler is still needed for 1490 nm downstream and 1310 nm upstream signals.

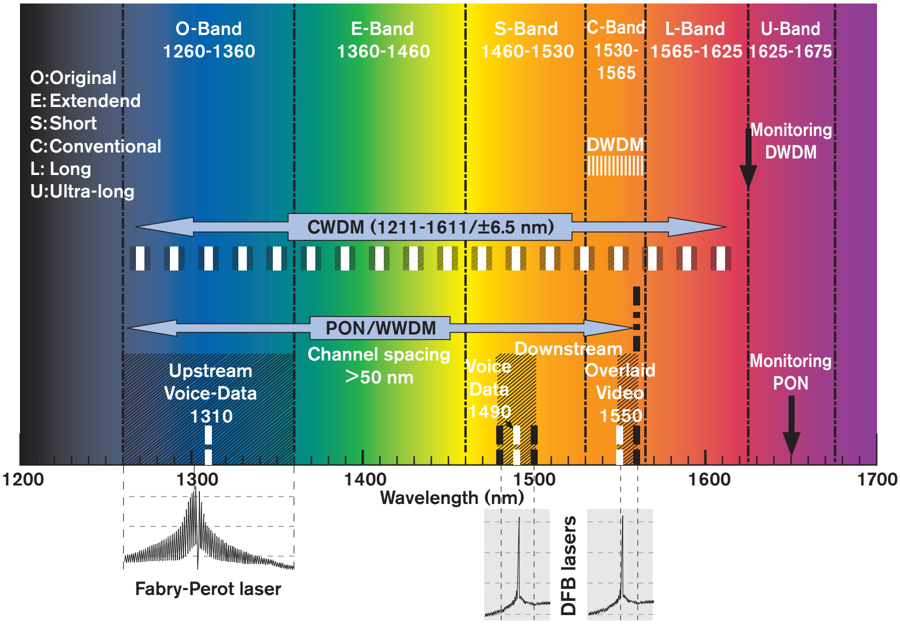


Figure 2.5 – FTTH P2MP PON wavelength allocation

Chapter 2

Chapter 3

Network Design and Engineering

This chapter examines the detailed architecture used in FTTH PONs; namely, the design and engineering of a PON, including a detailed description of the various components and protocols used.

3.1 PON Technology

At the CO, the public switched telephone network (PSTN) and Internet services are interfaced with the optical distribution network (ODN) via the OLT. In a P2MP PON, the downstream 1490 nm wavelength and upstream 1310 nm wavelength are used to transmit data and voice. The downstream 1550 nm wavelength can be used for analog video overlay. Multiple ONTs are connected to each PON through one or more splitters. In a P2P system, the voice and data are transmitted on the same 1310 nm wavelength downstream and upstream because it uses a fiber pair; one fiber downstream and another one upstream. For analog overlay video, 1550 nm is still used in the same configuration as for P2MP.

Figure 3.1 shows a detailed view of the main components of a PON, and Figure 3.2 shows an example of the physical-layer P2MP FTTH PON topology.

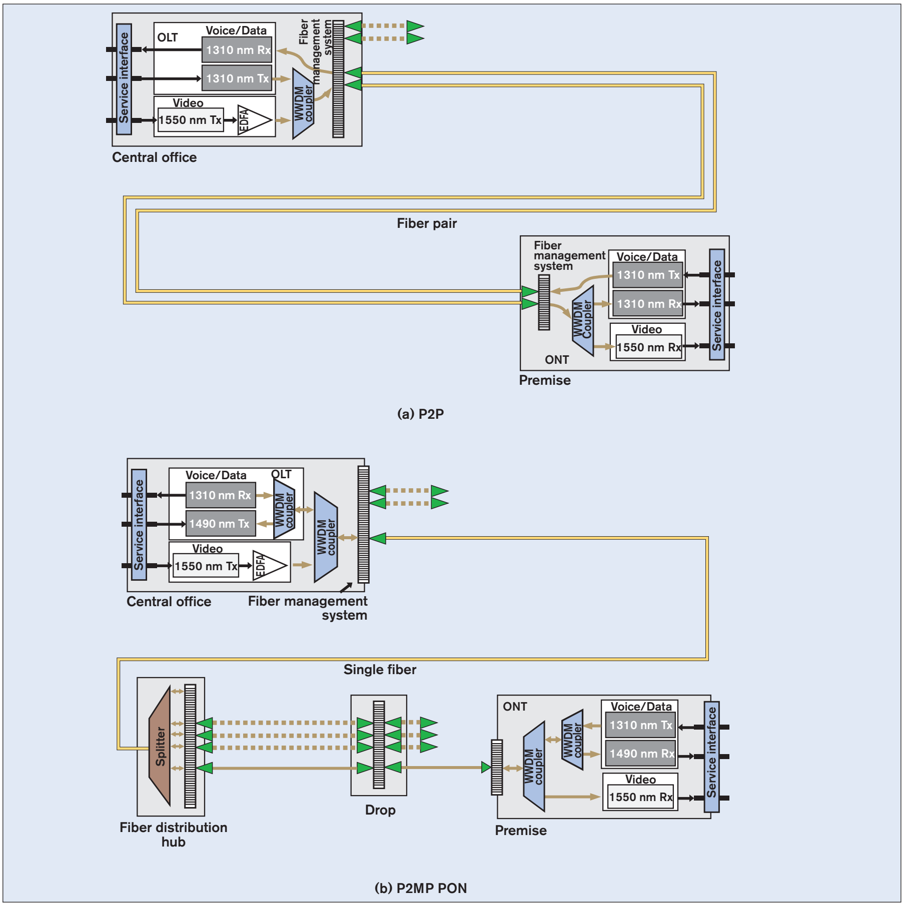


Figure 3.1 – Main PON components – basic system architecture [Pv1_37]

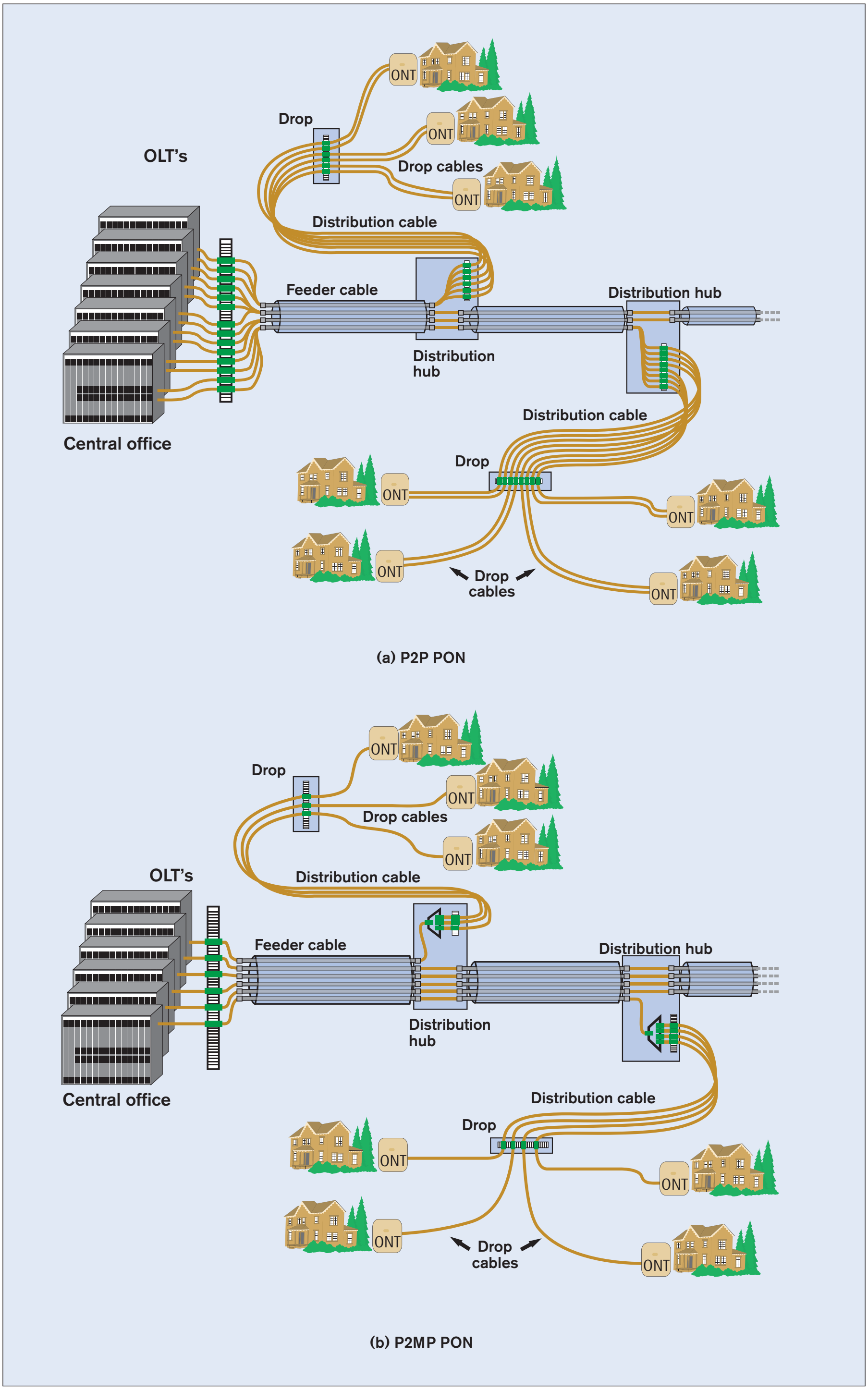


Figure 3.2 –Physical-layer PON topology

There are different types of PONs currently being deployed, each based on different technologies and standards. For P2P PONs, standards specify transmitting different types of services (voice and data) on the same wavelength over a fiber pair, whereas for P2MP PONs, two wavelengths with channel spacing wider than 50 nm (i.e., WWDM) are used to transmit the services over a single fiber. In both cases, this applies to upstream and downstream transmission. Also, any existing video signal is transported over a different wavelength (1550 nm), currently in an overlaid analog format.

One of the most mature and currently used PON systems is broadband PON (BPON), based on the ITU-T G.983 series of recommendations. BPON uses ATM as the transport protocol (see Table 3.1) with symmetric and asymmetric data rate combinations of 155.52 and 622.08 Mb/s. Later, 1244.16 Mb/s was also added, but for asymmetric downstream transmission only. BPON transparently transports any type of data, regardless of the type of data link frame.

Another system that was added on after BPON is Gigabit-capable PON (GPON). GPON is based on the ITU T G.984 series of recommendations. It provides a great deal of flexibility, transporting any type of data using ATM and/or GPON encapsulation method (GEM), which encapsulates different types of data. GPON provides several possible combinations of upstream and downstream data rates (up to 2488.32 Mb/s downstream) and may use forward error correction (FEC), if required.

Ethernet PON (EPON), on the other hand, is based on the IEEE 802.3ah-2004 specification developed by the Ethernet in the First Mile Alliance (EFMA) community[12]. EPON is designed for simplicity and allows packet-based transmission upstream and downstream at a symmetric rate of 1250 Mb/s (1000 Mb/s nominal) with optional FEC. The multipoint media access control (MAC) protocol (MPCP) in EPON controls access to a P2MP architecture (1000BASE-PX10 for up to 10 km reach, and 1000BASE-PX20 for up to 20 km), making the P2MP network appear to the higher protocol layers as a collection of P2P links (P2P link emultion).

FEC is used by the transport layer in communication systems and is based on transmitting data in an encoded format (block-based code). The most common code uses the Reed-Solomon format, and is 255 bytes long. It introduces redundancy (adds an extra 16 redundant overhead bits at the end of a constant-size block of 239 data bytes), allowing the decoder to detect and correct transmission errors (BER from 10^{-4} – the worst case – to an improved 10^{-15}). FEC can be used with GPON and EPON using Fabry-Perot lasers, especially to reduce system penalty due to the mode partitioning noise (MPN) typical of that laser and, consequently, to increase the maximum reach (maximum distance between the OLT and the ONTs) and/or the split ratio using the same transceiver equipment (but at the expense of some loss of capacity, as it introduces extra overhead).

[12] *www.efma.org*

For all three types of PONs, downstream voice/data transmission is performed over a continuous bit stream. Upstream transmission, from one ONT at a time, is performed either over a delayed or burst bit stream, as shown in Table 3.1.

Table 3.1 – PON requirement characteristics

	Traffic Direction		BPON	GPON	EPON	Standards Recommendations
	Down	Up				
Bit Stream	X		Continuous			BPON : ITU -T Rec. G.983 .x GPON : ITU -T Rec. G.984 .x EPON : IEEE802.3ah -2004
		X	Delayed			
			Burst			
Protocol/ Modes	X		ATM	ATM GEM Dual	Ethernet 802.3 MPCP (FEC optional)	
		X		ATM GEM		

(a) Bit stream and protocol

	Traffic Direction		BPON	GPON	EPON
	Down	Up			
Bit Rates (Mb/s)	155.52		In ITU-T Rec. G.983.1		
	622.08	155.52			
	622.08				
	1244.16	155.52		In ITU-T G.984.2	
	1244.16	622.08			
	1244.16				
	2488.32	155.52			
	2488.32	622.08			
	2488.32	1244.16			
	2488.32				
	1000 nominal				In IEEE802.3ah

(b) Bit rates

	BPON	GPON	EPON	Notes	Standards Recommendations
Logical/ Maximum Physical Distance (km)		10		Fabry-Perot laser 1244.6+ Mb/s	GPON: G.984.2
			10		EPON: IEEE802.3ah 1000BASE-PX10
	20				BPON: G.983.1
		60/20		Different fiber types / FFS	GPON: G.984.2
			20		EPON: IEEE802.3ah 1000BASE-PX20

GPON: Maximum $L_{OLT\text{-}LastONU}$ = 60 km
Maximum $L_{OLT\text{-}LastONU}$ = 20 km

FFS: For further study

(c) Maximum reach

Standards Recommendations		Split Ratio BPON	GPON	EPON	Notes
IEEE802.3ah	100BASE-PX10			16/32[1]	[1]with FEC
	100BASE-PX20			16	
ITU-T G.983.1		16/32			
ITU-T G.984.2			16/32/64		

(d) P2MP split ratio

	Type/Specifications	Standards Recommendations
Fiber	ITU-T Rec. G.652A/C; Rec. G.982	
	IEC 60793-2 Optical Fibers - Part 2-50: Product specifications - Sectional specification for class B single-mode fibers	IEC 60793-2-50 Type B1.1 Dispersion un-shifted single-mode fiber
		IEC 60793-2-50 Type B1.3 Dispersion un-shifted low-water peak single-mode fiber

(e) Fiber

Wavelength Bands Tx-Rx Types	BPON	GPON	EPON
1260-1360 nm[1]	Upstream		
Tx	FP DMU		
Rx	PIN		
1360-1480 nm	Intermediate band/FFU		
Tx/Rx	Downstream/TBS		
1480-1500 nm	1550-Basic band		
Tx	Downstream: DFB DMC (10km/GPON/EPON = FP DMU)		
Rx	PIN (APD = GPON 2.5G/EPON 20km)		
1480-1580 nm			
Tx/Rx	Downstream/TBS		
1539-1565 nm	1550-Enhancement band/ADS		
Tx/Rx	Downstream/TBS		
1550-1560 nm	1550-Enhancement band/VDS		
Tx	DFB EMC		
Rx	APD		
L-band	TBS/FFU		
Tx/Rx	Downstream/TBS		

[1] The wavelength is also used downstream in P2P PON
ADS: Additional digital services
APD: Avalanche photodiode
DFB: Distributed feedback
DMC: Directly modulated, cooled
DMU: Directly modulated, uncooled
EMC: Externally modulated, cooled
FFU: For future use
FP: Fabry-Perot
Rx: Receiver
Tx: Transmitter
TBS: To be specified
VDS: Video distribution service

(f) Wavelength Bands

Specifications (dB)		ITU-T			EPON		
		Class	G.983.1 G.982[1] G.983.3 BPON	G.984.2 GPON	Class	IEEE 802.3ah-2004 1000BASE- PX10	PX20
Link ORL	Min/Max		32			20/15	
Link attenuation[2]		A	5/20			5/19.5D;20U	
		B	10/25				10/23.5D;24U
		C	15/30				

[1] ITU-T Rec. G.982, “Optical access networks to support services up to the ISDN primary rate or equivalent bit rates” (11/96)
[2] IEEE uses channel loss instead of link attenuation in ITU-T

(g) Link optical return loss and attenuation

Bit rate (Mb/s)	Class	Tx Averaged Launch Power (dBm) 1260-1360 nm OLT Min	OLT Max	ONT Min	ONT Max	Standards BPON/GPON: ITU-T Rec. EPON: IEEE 802.3ah	
155.52	A	-	-	-/-6	-/-1	BPON/GPON: G.983.1/G.984.2	
	B	-4/-	+1/-	-4	+1		
	C	-2/-	+3/-	-2	+3		
622.08	A	-7/-	-2/-	-6	-1		
	B	-2/-	+3/-	-1	+4		
	C						
1000 nominal		-3	+2	-1	+4	EPON	1000BASE-PX10
		+2	+7				1000BASE-PX20
1244.16	A	-4	+1	-/-3	-/+2	BPON: G.983.1/ GPON: G.984.2 (Down&Up/10km)	
	B	+1	+6	-/-2	-/+3		
	C	+5	+9	-/+2	-/+7		
2488.32	A	0	+4	FFS		GPON: G.984.2 [1]DFB+APD/DFB/SOA+PIN	
	B	+5	+9				
	C	+3/+8[1]	+7/12[1]				

(h) Transmitter launch power for P2P PON

Bit rate (Mb/s)	Class	Tx Averaged Launch Power (dBm)				Standards BPON/GPON: ITU-T Rec. EPON: IEEE 802.3ah
		OLT		ONT		
		Min	Max	Min	Max	
		1480-1580 nm		1260-1360 nm		
155.52	A	-/-7.5	-/-3	-/-7.5/-6	0	BPON: G.983.1/G.983.3/G.984.2
	B	-4/-2.5	+2	-4/-5.5/-4	+2	
	C	-2/-0.5	+4	-2/-3.5/-2	+4	
622.08	A	-7/-5.5	-1	-6/-	-1/-	
	B	-2/-0.5	+4	-1/-	+4/-	
	C					
		1480-1500 nm				
1000 nominal		-3	+2	-1	+4	EPON 1000BASE-PX10
		+2	+7			EPON 1000BASE-PX20
1244.16	A	-4	+1	-/-3	-/+2	BPON: G.983.1/ GPON: G.984.2 (Down&Up/10km)
	B	+1	+6	-/-2	-/+3	
	C	+5	+9	-/+2	-/+7	
2488.32	A	0	+4	FFS		GPON: G.984.2 [1]DFB+APD/DFB/SOA+PIN
	B	+5	+9			
	C	+3/8[1]	+7/12[1]			

(i) Transmitter launch power for P2MP PON

Bit rate (Mb/s)	Class	Minimum Receiver Power (dBm)				Standards BPON/GPON: ITU-T Rec. EPON: IEEE 802.3ah
		1260-1360 nm				
		OLT		ONT		
		Sensitivity	Overload	Sensitivity	Overload	
155.52	A	-/-28.5	-/-8	-/-27	-/-6	BPON: G.983.1/G.984.2
	B	-30/-28.5	-8	-30	-8/-9	
	C	-33/-31.5	-11	-33	-11/-12	
622.08	A	-28/-26.5	-6	-27	-6	BPON: G.983.1/G.984.2
	B					
	C	-33/-31.5	-11	-32	-11	
1000 nominal		-24		-24		EPON 1000BASE-PX10
				-27		EPON 1000BASE-PX20
1244.16	A	-25	-4	-/-24	-/-3	BPON: G.983.1/ GPON: G.984.2 (Down&Up/10km)
	B			-/-28	-/-7	
	C			-/-29	-/-8	
2488.32	A	0	+4	FFS		GPON: G.984.2 [1]DFB+APD or DFB/SOA+PIN
	B	+5	+9			
	C	+3	+7			

FFS: For further study

(j) Receiver sensitivity and overload for P2P PON

<table>
<tr><th rowspan="3">Bit rate (Mb/s)</th><th rowspan="3">Class</th><th colspan="4">Minimum Receiver Power (dBm)</th><th rowspan="3" colspan="2">Standards
BPON/GPON: ITU-T Rec.
EPON: IEEE 802.3ah</th></tr>
<tr><th colspan="2">OLT(1480-1500 nm)</th><th colspan="2">ONT(1480-1500 nm)</th></tr>
<tr><th>Sensitivity</th><th>Overload</th><th>Sensitivity</th><th>Overload</th></tr>
<tr><td rowspan="3">155.52</td><td>A</td><td>-/-28.5</td><td>-/-8</td><td>-/-28.5</td><td>-/-5</td><td rowspan="3" colspan="2">B-PON: G.983.1/G.984.3</td></tr>
<tr><td>B</td><td>-30/-28.5</td><td>-8/-8</td><td>-30/-31.5</td><td>-8/-8</td></tr>
<tr><td>C</td><td>-33/-31.5</td><td>-11/-11</td><td>-33/-34.5</td><td>-11/-11</td></tr>
<tr><td rowspan="3">622.08</td><td>A</td><td rowspan="2">-28/-26.5</td><td rowspan="2">-6/-6</td><td rowspan="2">-27</td><td rowspan="2">-6</td><td rowspan="3" colspan="2">B-PON: G.983.1/G.983.3</td></tr>
<tr><td>B</td></tr>
<tr><td>C</td><td>-33/-31.5</td><td>-11/-11</td><td>-32</td><td>-11</td></tr>
<tr><td rowspan="2" colspan="2">1000 nominal</td><td rowspan="2">-24</td><td rowspan="2"></td><td>-24</td><td rowspan="2"></td><td rowspan="2">EPON</td><td>1000BASE-PX10</td></tr>
<tr><td>-27</td><td>1000BASE-PX20</td></tr>
<tr><td rowspan="3">1244.16</td><td>A</td><td rowspan="2">-25/-25</td><td rowspan="3">-4/-4</td><td rowspan="3" colspan="2"></td><td rowspan="3" colspan="2">B-PON: G.983.1/
G-PON: G.984.2
(Down&Up/10km)</td></tr>
<tr><td>B</td></tr>
<tr><td>C</td><td>-26/-26</td></tr>
<tr><td rowspan="3">2488.32</td><td>A</td><td>0</td><td>+4</td><td rowspan="3" colspan="2">FFS</td><td rowspan="3" colspan="2">G-PON: G.984.2
[1]DFB+APD or
DFB/SOA+PIN</td></tr>
<tr><td>B</td><td>+5</td><td>+9</td></tr>
<tr><td>C</td><td>+3</td><td>+71</td></tr>
</table>

FFS: For further study

(k) Receiver sensitivity and overload for P2MP PON

3.2 Active Equipment

Although passive optical networks (PONs) are consist mostly of passive components, the following active components are also required (see Figure 3 3):

- Located at the CO:
  - OLT (digital voice/data terminal equipment) using:
    - 1490 nm laser transmitter for P2MP PON; 1310 nm laser transmitter for P2P PON
    - 1310 nm detector receiver
  - Analog video terminal equipment (if analog video overlay is used) using:
    - 1550 nm laser transmitter
    - Erbium-doped fiber amplifier (EDFA) to amplify the video signal
- Located at each subscriber's premises:
  - ONU using:
    - Power supply
    - 1310 nm laser transmitter
    - 1490 nm receiver for P2MP PON; 1310 nm receiver for P2P PON
    - 1550 nm receiver for video reception
  - Battery backup (may be located inside or outside the subscriber's premises; may be under the subscriber's ownership/responsibility)

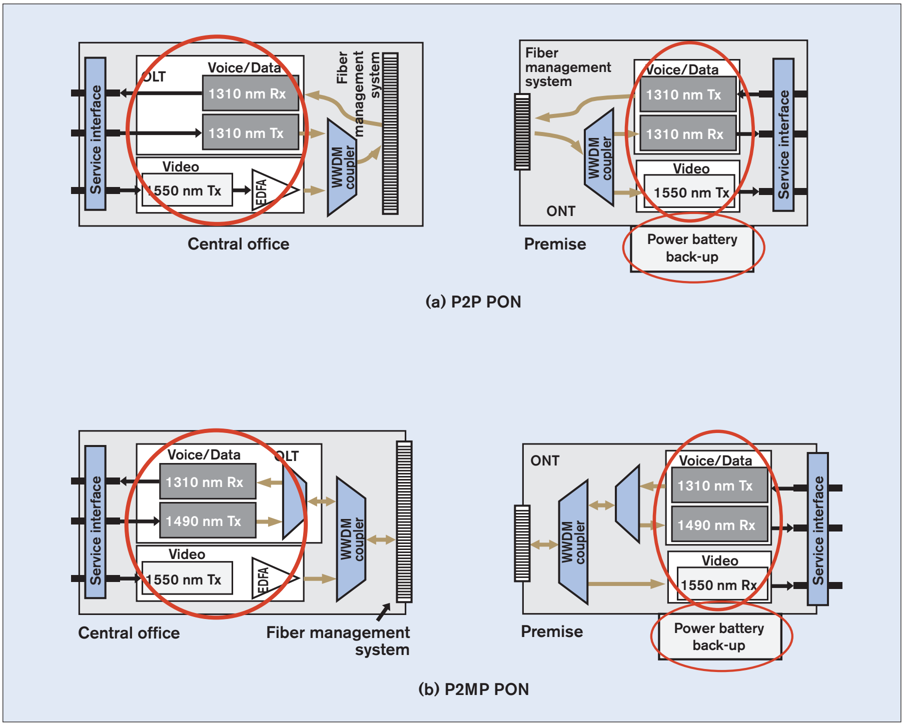


Figure 3.3 – PON active equipment for both P2P (a) and P2MP (b)

The drop fiber is brought to the ONT and the services are delivered inside the premises using conventional copper cabling, as shown in Figure 3.4. Figure 3.5 shows an example of an ONT whose power supply contains battery back-up.

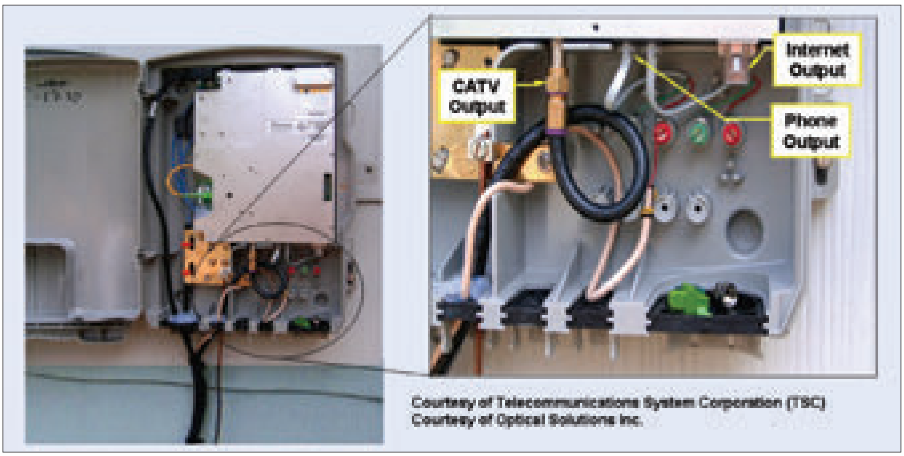


Figure 3.4 – Example of a PON ONT

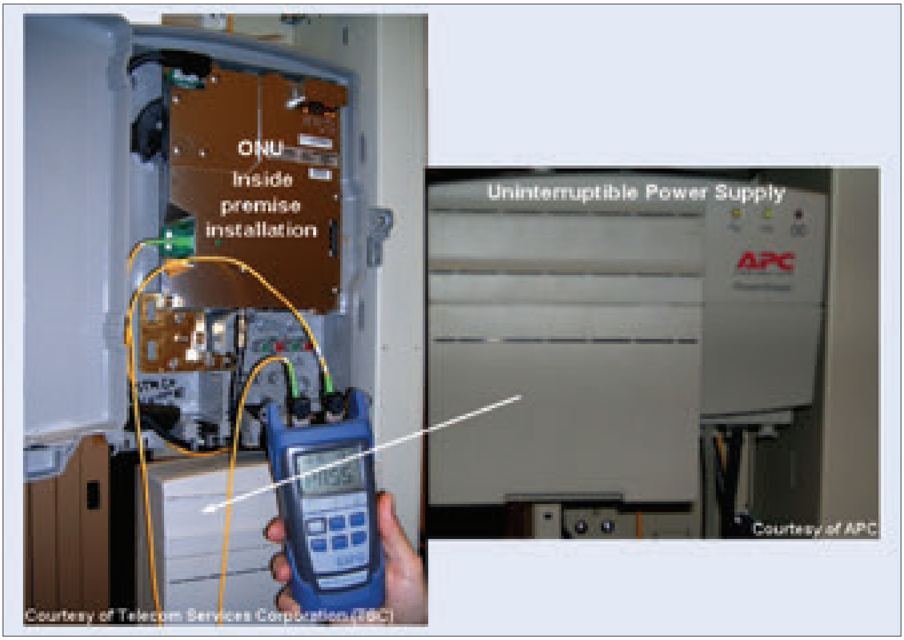
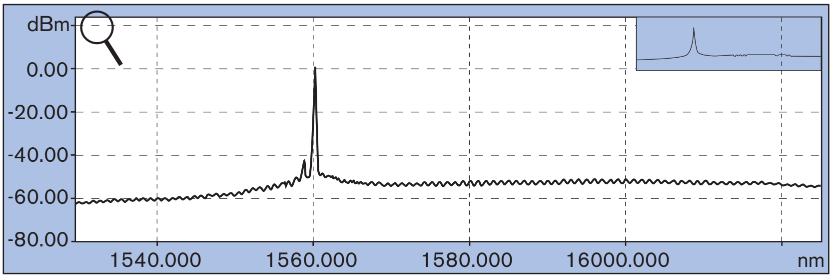


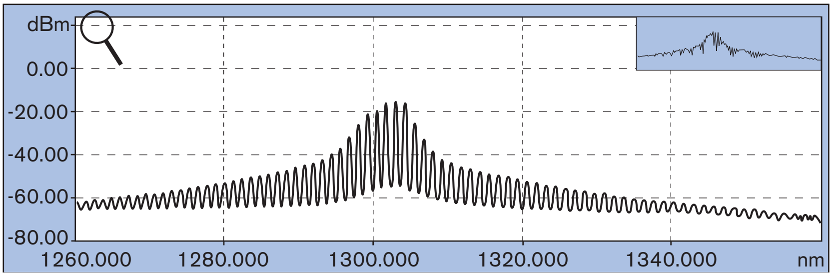
Figure 3.5 – Example of a PON power supply with battery backup

The downstream 1490 nm signal is transmitted using a directly modulated thermo-electrically cooled DFB laser. In most cases, the upstream 1310 nm signal is transmitted using a directly modulated uncooled Fabry-Perot laser. Analog overlaid video services are converted to optical format at the 1550 nm wavelength by the optical video transmitter using an externally modulated thermo-electrically cooled frequency-stabilized DFB laser. At present, there are no plans for upstream video transmission, though there have been discussions about this at the ITU-T (an amendment of Recommendation G.983.2 includes a provision for an upstream video return path, which would certainly be considered for digital and IP video transmissions).

Figure 3.6 shows typical spectra of DFB and Fabry-Perot lasers. DFB lasers are single longitudinal mode (SLM) lasers with a narrow, one-line spectrum (their spectral width is down in the 100 kHz to MHz range, when coherence control is provided) and are suitable for downstream transmission at high bit rates and high power levels for analog video overlay. Fabry-Perot lasers, on the other hand, are low-cost but transmit over a broad spectrum. Because Fabry-Perot lasers are multilongitudinal mode (MLM) lasers, the spectrum is not SLM or single-frequency but consists of periodic multilines (i.e., the line spacing is equal to c/2L, where c is the velocity of light in vacuum and L, the length of the laser cavity; the width of the lines is proportional to the transition time between the lasing energy levels).



(a) DFB laser



(b) Fabry-Perot laser

Figure 3.6 – Examples of wavelength spectra of the lasers used in FTTH PONs

Table 3.2 shows some of the critical issues concerning the downstream and upstream laser transmitters.

Table 3.2 – Critical transmitter issues

	Downstream		Upstream
	Voice/Data DFB	Video DFB	Voice/Data Fabry-Perot
Center Wavelength/Frequency	Tight		Loose
Spectral Width	Narrow		Wide
Frequency stability/Temperature control	Yes		No
Output power stability control	Yes		
Reliability	High		Critical
Environmental category	Controlled		Outside plant Uncontrolled
Cost	Mid	High	Low

EPON 1000BASE-PX20 will use a DFB laser for upstream transmission

3.2.1 OLT and ONT

Because the downstream power is divided among the ONTs by the splitter, FTTH P2MP PONs have considerable optical loss. In order to ensure that each branch of the P2MP PON will operate correctly and meet all specifications, the network designer must establish an optical loss budget. The loss budget specifies the minimum and maximum amount of loss (margin) that can be tolerated in the PON between the OLT and any ONT (the same case applies to P2P PON).

Table 3.1 (g) shows the loss budget requirements for optical return loss (ORL) and attenuation for the three ODN classes (A, B and C) defined for BPON and GPON by the ITU-T, as well as channel loss requirements for EPON (different expressions may be used by different standards organizations to describe the same feature – uniformity in terminology and symbology is always encouraged but not necessarily guaranteed). It is interesting to note that the two loss categories required by EPON correspond to Class A and B for BPON and GPON. For BPON and GPON, Class C is the most demanding and therefore requires the most expensive transceivers, but it accepts the greatest loss, allowing for a greater reach and/or split ratio. 1000BASE-PX20 offers similar advantages for EPON. By ensuring that the PON will meet the requirements for the desired class, the designer ensures that the power levels received by the ONTs and by the OLT will be sufficient for reliable, bidirectional communication.

Attenuation is the total loss of optical energy between the transmitter and the receiver, end-to-end. Attenuation in a PON is due to backscattering of the light as it travels along the optical fiber and to the insertion loss (IL) of each component; that is, the loss of optical energy resulting from the insertion of each component into the optical path. Optical return loss (ORL) is a measure, from one end, of the total energy reflected back to the source by all the interfaces due to a variation of the index of refraction, breaks, discontinuities, voids, Fabry-Perot etalon, etc. created inside a component or along a link.

The OLT and ONT transmitter characteristics are shown in Table 3.3 and power requirements in Table 3.1 (i) for P2P and (j) for P2MP PON respectively.

Table 3.3 – OLT and ONT characteristics

Terminal equipment	Services	Wavelength (nm)		Laser			Issues
		Typ.	Range	Type	Output power (dBm)	Maximum linewidth (nm)	
OLT (Downstream)	Voice Data	1490	1480-1500	DFB[1]	see Table 3-5	1	CD[2]
	Video	1550	1550-1560	DFB[3]	+21	1	Safety CD[2] SBS[4] CSO[5]
ONT (Upstream)	Voice Data	1310	1260-1360 (1300-1324[9])	FP[6] DFB[7]	see Table 3-5	5.8 RMS	MPN[2,8] MH[2,10]

1 DFB: Distributed feedback single longitudinal mode (SLM) laser, cooled, directly modulated
2 CD: Chromatic dispersion – only at high bit rates (1.25 Gb/s and 2.5 Gb/s)
3 DFB SLM laser, cooled, externally modulated, filtered
4 SBS: Stimulated Brillouin backscattering; not a problem for directly modulated DFB (chirp sufficiently spreads laser spectrum to suppress SBS); a problem for narrow linewidth externally modulated DFB (SBS starts at ~+10 dBm). Suppression technique required.
5 CSO: Composite second-order beat noise
6 FP: Fabry-Perot multilongitudinal mode (MLM) laser, uncooled, directly modulated (for BPON, GPON and 1000BASE PX10 EPON upstream transmission at 1310 nm)
7 DFB laser required for 1000BASE PX20 EPON
8 MPN: Mode partitioning noise
9 Practical range
10 MH: Mode-hopping

The OLT and ONT lasers consist of DFB and FP lasers, both of which are semiconductor lasers (called diode lasers or laser diodes). The difference between the two types is essentially related to the DFB design, in which a grating is inscribed in the semiconductor in order to select only one mode from the lasing process (typically, in a FP laser if no grating is used, mode-hopping occurs). Figure illustrates the lasing mechanisms from the spontaneous emission to the stimulated emission. The figures below also show the typical single transverse mode that is spatially generated from the laser cavity.

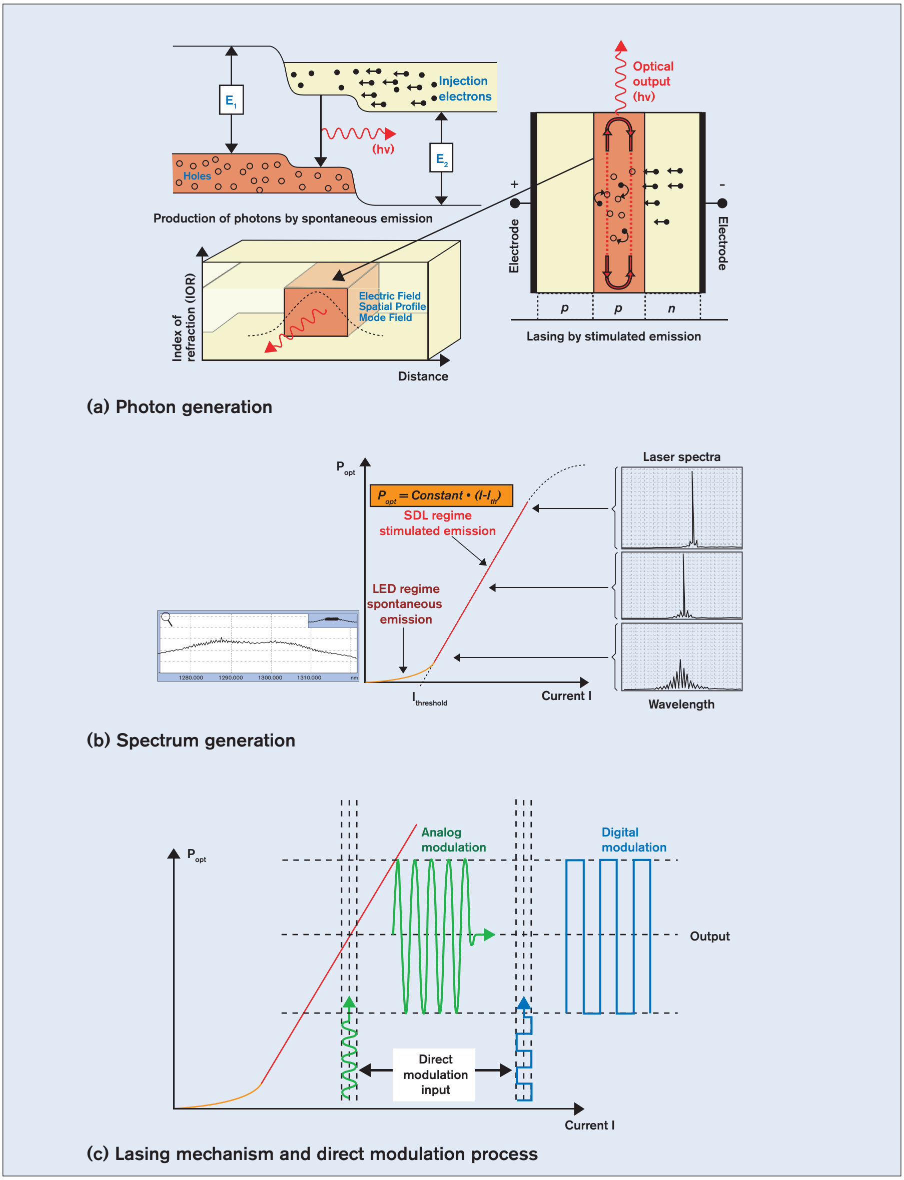


Figure 3.7 – Lasing mechanism in a semiconductor

Table 3.1 (j) and (k) show the OLT and ONT receiver sensitivity and overload requirements for P2P and P2MP, respectively. Receivers must be operated within their specified optical power range. If the optical power level at the receiver is too high or too low, the bit error rate (BER) will increase.

ITU-T Recommendation G.983.3 Amendment 2 establishes requirements for video transmission (see Table 3.4).

Table 3.4 -- G.983.3 BPON video transmission

Downstream Video Type	Terminal	Bit Rate (Mb/s)	Wavelength (nm)	Power (dBm)				Loss (dB)		ITU-T Rec.
				Tx		Rx Min.		Min	Max	
				Min	Max	Sens.	Over.			
Analog Overlaid	OLT	Tx: 622.08	1490	0	+3			9	27	B-PON: G.983.3 Amd. 2
		Rx: 155.52	1310			-32	-9	13	29	
Digital		Tx: 622.08	1490	+1	+4			10	28	
		Rx: 155.52	1310			-31	-6			
	ONT	Tx: 155.52	1310	-2	+4					
		Rx: 622.08	1490			-28	-6			

3.3 Passive Optical Components[1]

The main passive components in a PON are the following (illustrated Figure 3.8):

- 1 x 2 WWDM coupler(s) (two couplers if analog video is used in P2MP)
- 1 x N splitter (in P2MP)
- Fiber-optic cables (feeder, distribution and drop)
- Connectors and cable assemblies
- Fiber management systems/enclosures
  - Fiber distribution hub/splitter enclosure
  - Fiber distribution drop/drop enclosure

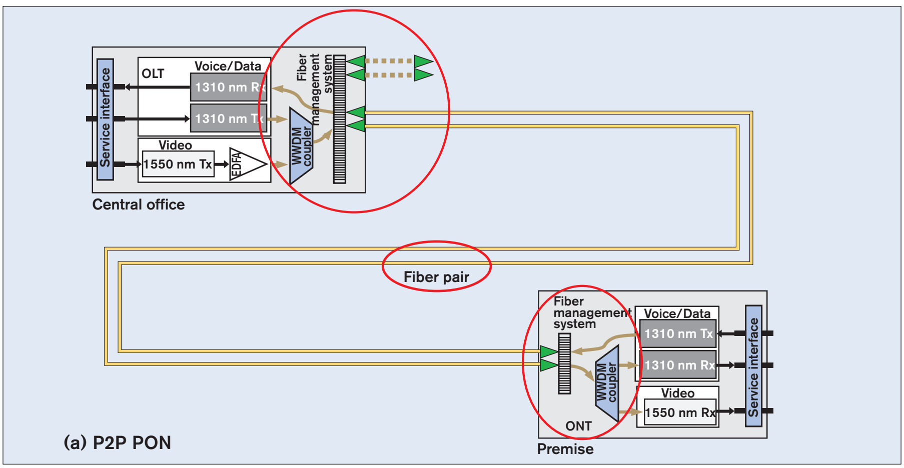


Figure 3.8a – PON passive components

[1] *The optical fiber/cable is considered separately in the next section*

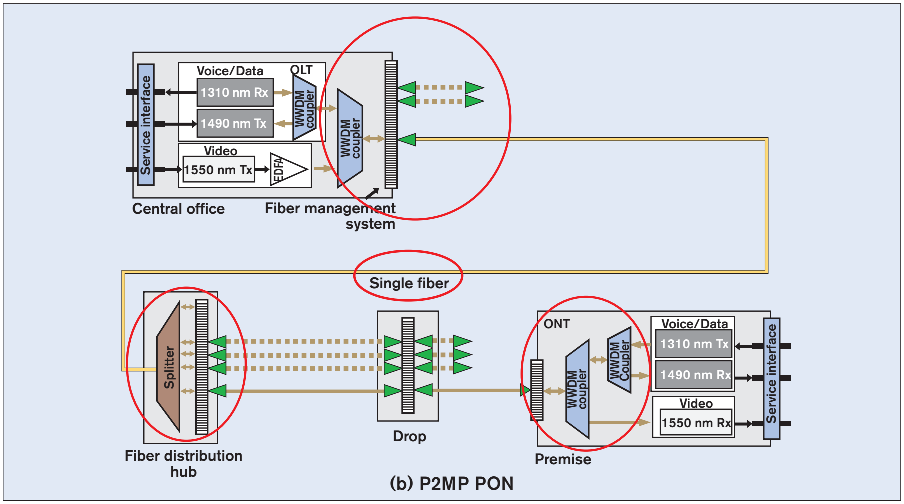


Figure 3.8b – PON passive components

The two most critical passive optical components in the FTTH P2MP PON are the WWDM coupler(s) and the splitter.

The 1 x 2 WWDM coupler used in a P2MP PON is bidirectional and typically exhibits an insertion loss (IL) of 0.7 to 1.0 dB. This component is used in a controlled environment inside the CO and in an uncontrolled environment inside the ONU. At the CO, the coupler has high input power at 1550 nm (the one after the EDFA can be subject to +21 dBm at its input).

The functions of the WWDM coupler are the following:

- Couples the high power video signal with the OLT voice/data signal for downstream transmission at the CO
  - 1550 nm and 1310 nm in P2P on one of the two fibers
  - 1550 nm and 1310 nm/1490 nm in P2MP on the single fiber
- Couples the video signal with voice/data signal in the ONT
  - 1550 nm and 1310 nm in P2P on the same fiber above from the CO
  - 1550 nm and 1310 nm/1490 nm in P2MP
- Couples the voice/data signal for downstream and upstream transmissions
  - Not necessary in P2P
  - 1310 nm and 1490 nm in P2MP
- Transmits the upstream voice/data signal to the receiver in the OLT

Used in an uncontrolled outside plant environment (enclosure protected), the splitter in a P2MP PON is typically a bidirectional, broadband component with high loss (up to 18 dB for 1:32 split ratio) and average input power at 1550 nm and 1310 nm (could be high power at 1550 nm if close to CO).

The 1 x N splitter functions (only in P2MP) are the following:

- Splits the downstream coupled video and voice/data signals to N subscriber ONTs
- Transmits the upstream voice/data signal from N subscriber ONTs to the OLT

Table 3.5 presents critical performance requirements for both the coupler and the splitter.

Table 3.5 – Examples of PON coupler and splitter technical requirements

Parameters		WWDM Coupler	Splitter
Coupling/Splitting ratio (as example)		2x1	1x4; 1x8; 1x16; 1x32
Wavelength range (nm)	Upstream	1260-1360	
	Downstream	1480-1500[1]	
		1550-1560	
Insertion loss (IL) (dB)		< 1	< 18 (1x32)
Loss uniformity (dB)		< 0.5	< 1.3 (1x32)
ORL (dB)		> 55	
Directivity (dB)		> 55	
Polarization dependent loss (PDL) (dB)		< 0.2	
Packaging		As small as possible	
Reliability		As high as possible at affordable cost	
Network support		Survivability and protection	

Various technologies are available for coupler and splitter designs:

- Thin-film filter (TFF)
- Gratings
  - Bulk diffraction grating (BDG)
  - Fiber Bragg grating (FBG)
- Fiber-based
  - Fused biconic tapered (FBT) fiber
- Waveguides based on a planar lightwave circuit (PLC)

These technologies have various advantages and disadvantages as shown in Table 3.6.

Table 3.6 – WWDM coupler and splitter technology comparisons

Technology	Particularities	Advantages	Disadvantages
Fused biconic tapered (FBT) Fiber	Two specialty fibers fused within a specific coupling/splitting region	Fiber based	Complex design at large coupling/splitting ratio
Planar lightwave circuit (PLC) -deposition -ion-exchange	Semiconductor chip fabrication technology	Economy of scale	Non-recurring cost during design phase
		Cost effective at large coupling/splitting ratio	Polarization effects for deposition techniques
			Connectivity with fiber for deposition techniques
Thin-film filter (TFF)	Technology known for years	Cost effective at small coupling/WDM ratio	Complex design at large coupling/WDM ratio
Grating	Bulk Diffraction	Mastered technology	Operate by reflection
	Fiber Bragg	Fiber based	Complex expensive design
			Operate by reflection

3.3.1 Coupler

Figure 3.9 illustrates a TFF-based three-port WDM coupler (filter configuration). By adjusting the layer deposition, the spectral width of the filter may be adjusted. Various wavelength ranges may be used and controlled. Figure 3.10 shows the characteristics of a WWDM coupler based on thin-film technology. FBT technology may also be used for WWDM couplers (see Figure 3.13).

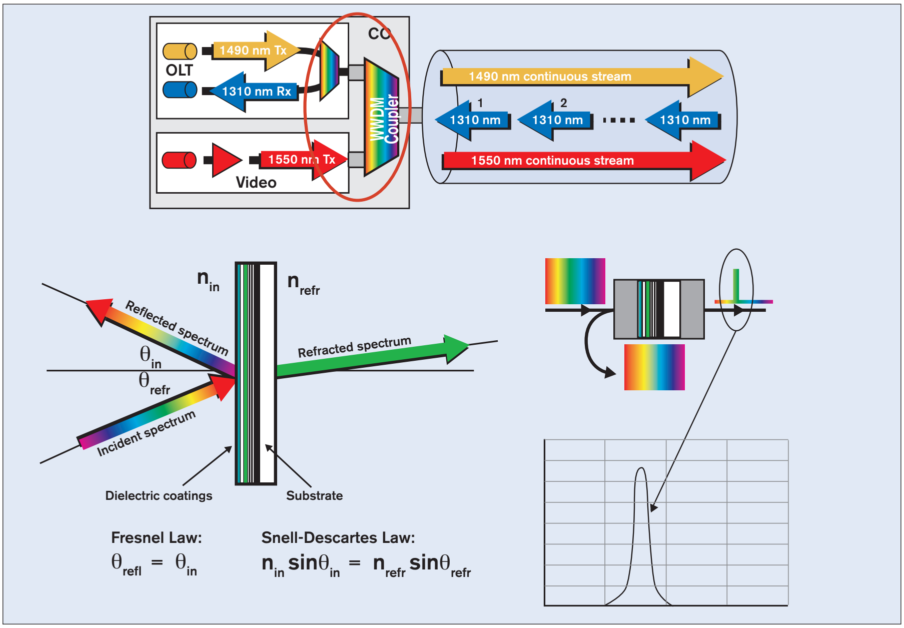


Figure 3.9 – Bidirectional Wide WDM (WWDM) three-port thin-film-filter coupler

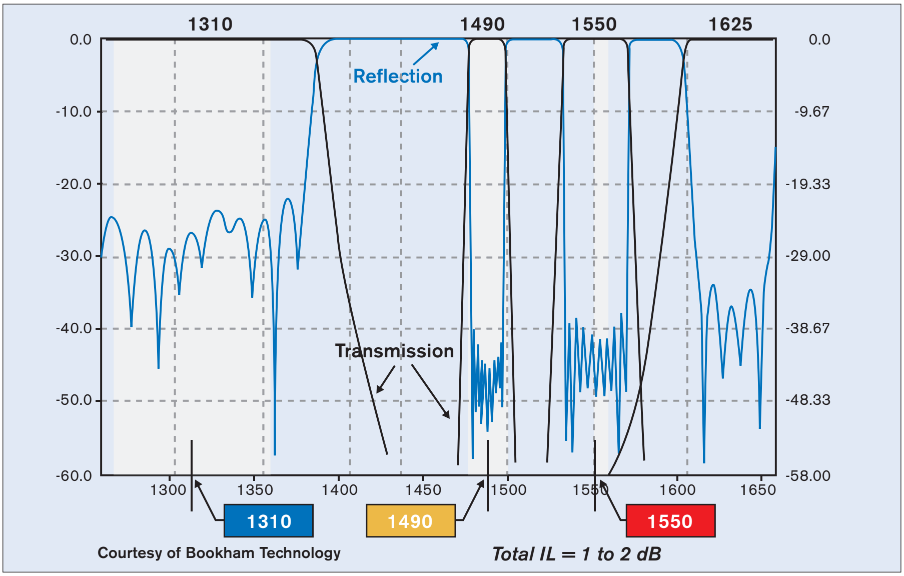


Figure 3.10 – Characteristics of typical PON WWDM coupler based on thin-film–filter technology

3.3.2 Splitter

In order for the subscribers to share the available total bandwidth, a bidirectional 1xN splitter is used in a P2MP PON. Figure 3.11 illustrates a typical splitter configuration.

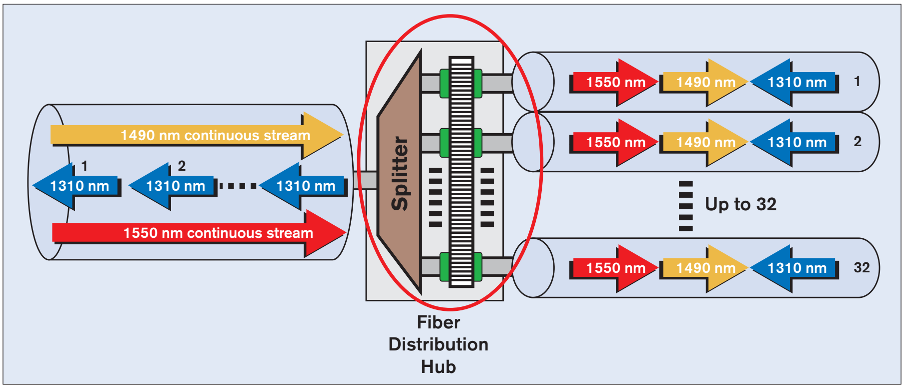


Figure 3.11 – Bidirectional 1 x N PON splitter

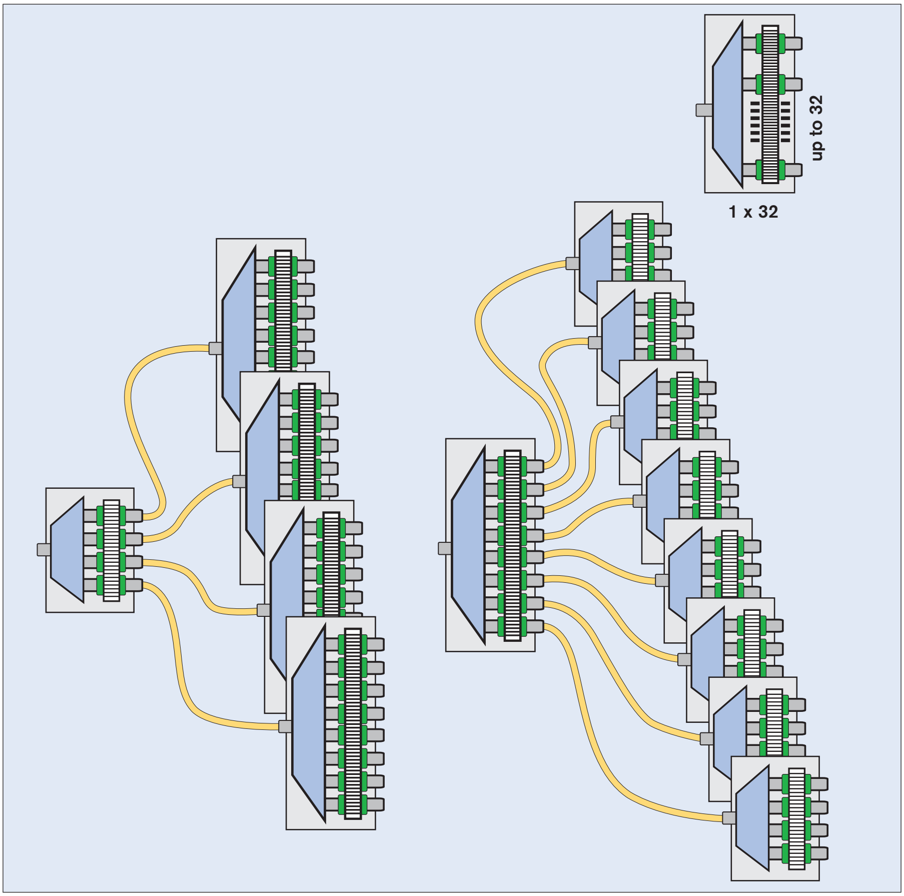


Figure 3.12 – Examples of various 1 x 32 PON splitter topology

The splitter is a bidirectional broadband branching device that has one input port and multiple output ports. The input (downstream) optical signal is divided among the output ports, allowing multiple users to share a single optical fiber and consequently share the available bandwidth of that fiber. In the upstream direction, optical signals from a number of ONTs are combined into the single fiber.

Splitters are passive devices because they require no external energy source other than the incident light beam. They are broadband and only add loss, mostly due to the fact that they divide the input (downstream) power. Splitter loss is usually expressed in dB and depends mainly on the number of output ports (about 3 dB for each 1 x 2 split). It should be noted that, contrary to what one might expect, the splitter adds approximately the same loss for light traveling in the upstream direction as it does for downstream direction.

There may be one splitter or several cascaded splitters in an FTTH PON, depending on the network topology (see Figure 3.12). ITU-T Recommendation G.983 currently allows split ratios up to 32, while Recommendation G.984 extends this to up to 64 splits. Regardless of the topology, the splitter must accommodate the allowed optical loss budget (Table 3.1 (g)).

Splitters can be packaged in different shapes and sizes depending on the basic technology used. The most common types are the planar waveguide (typically used for high split counts) and the fused biconic tapered (FBT) fiber coupler (typically used for relatively low split counts). Both types are manufactured for mounting in closure tray assemblies.

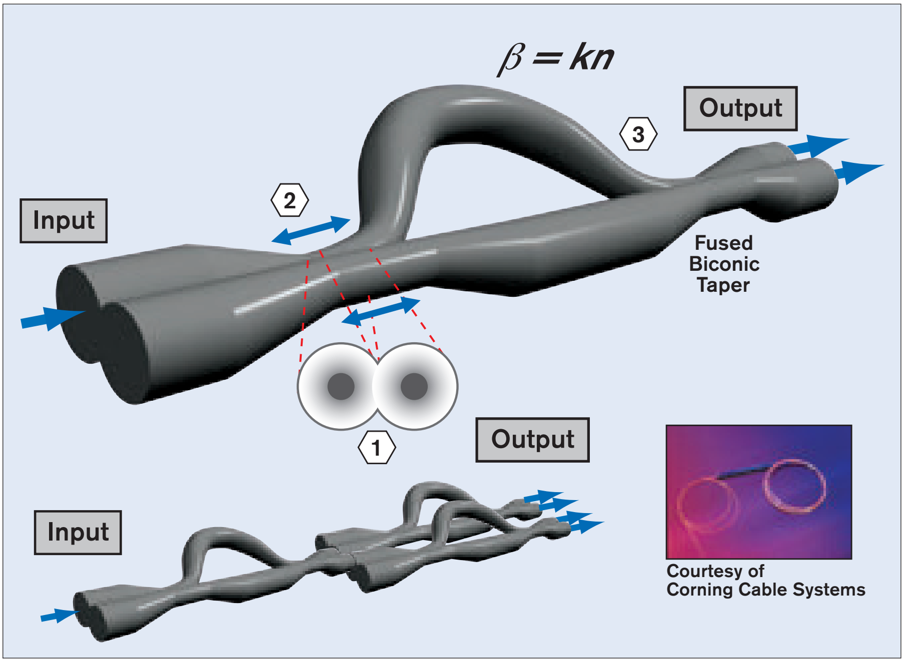


Figure 3.13 – Splitter design based on fused biconic tapered fiber (2 x N ratio is possible)

Figure 3.13 illustrates the FBT fiber technology. The amount of light coupled varies with the core-to-core proximity (1), the interaction length (2) and phase ß (3). Table 3.7 shows typical specifications for this type of splitter.

Table 3.7 -- Typical specifications of a fused biconic tapered (FTB) splitter

Parameter		1x4	1x8	1x16	1x32
Wavelength (nm)		1310/1550			
Bandpass (nm)		±40			
IL_{max} (dB)		7	10.75	14.8	18.5
$Uniformity_{max}$ (dB)		0.9	1.25	1.7	2.4
PDL_{max} (dB)		0.3	0.5	0.6	0.7
Directivity (dB)		>55			
Return Loss (dB)					
T° (°C)	Storage	-40 to 85			
	Operating				

Note: Splitter configuration of 0xN may also b used for PON redundancy protection

Courtesy of Gould Fiber Optics

Figure 3.14 below illustrates the planar lightwave circuit (PLC) technology. The PLC splitter consists of an optical circuit on a wafer (Si, for instance) made using tools and processes from the semi-conductor industry. Two techniques are used: deposition (such as chemical vapor deposition) and ion-exchange. Wafers offer economy of scale since multiple components are fabricated and inter-connected at once. However, they are sensitive to polarization effects.

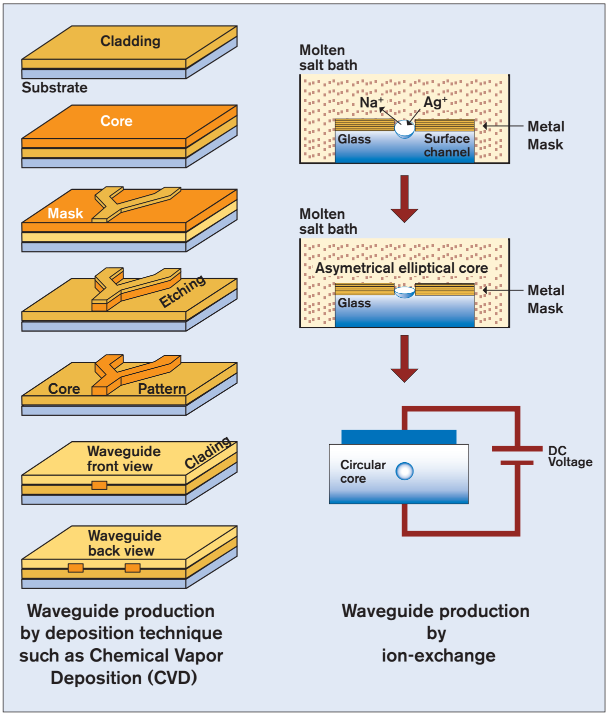


Figure 3.14 – Splitter design based on a planar lightwave circuit (PLC)

Table 3.8 illustrates the critical issues of PON passive components.

Table 3.8 – Major optical issues for passive components [Pv1_54]

Issues	Coupler	Splitter	Connectors	Closures
IL (bidirectional)		very high 1x32		
RL (bidirectional)			APC Others	
PDL				
Group delay + ripple	1310 nm FP laser/high bit rate			
High optical power*	1550 nm	1550 nm close to CO	close to CO	
Cleanliness	if connectorized			
Environment		in closure	ONT	

Negligible	
Critical for specified case	
Very critical	
N/A	

* +21 to +23 dBm at 1550 nm at Video EDFA output

IL: insertion loss
RL: return loss
PDL: polarization dependent loss
APC: angled physical contact/angled polished connector

3.3.3 Connectors

Because of the high-power analog video signal that PONs will carry, the APC connector was chosen. The APC connector is an angled (8°) connector (as shown in Figure 3.15) and as such provides very low reflection (ORL) of 65 dB or better.

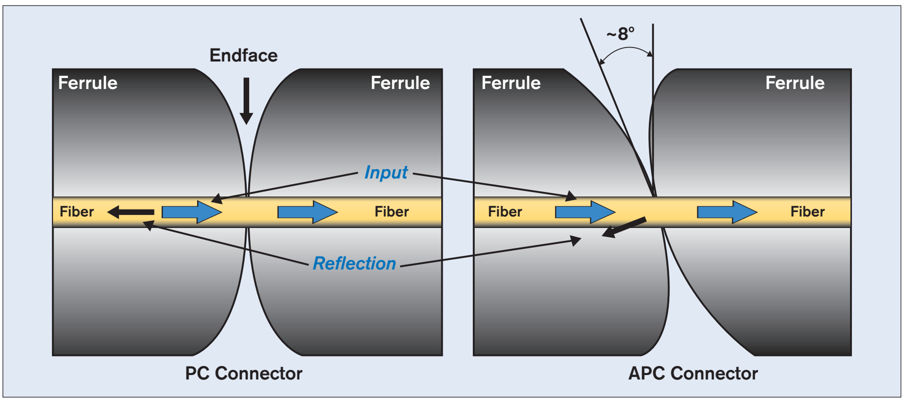


Figure 3 15 – Difference between PC and APC connectors

Small-form-factor connectors as shown in Figure 3.16 are preferable for PONs.

3.3.4 Enclosures

There are a number of enclosures used in PONs:

- The splitter enclosure (shown in Figure 3.17)
- The splice enclosure (shown in Figure 3.18) with buried and aerial installations
- The drop enclosure (shown in Figure 3.18)

There are two IEC standards that are particularly important for enclosures: IEC 61758-1 Ed.1.0, Interface standard for closures, General & Guidance, and IEC 62134-1, Fibre-optic enclosures, Generic Specification.

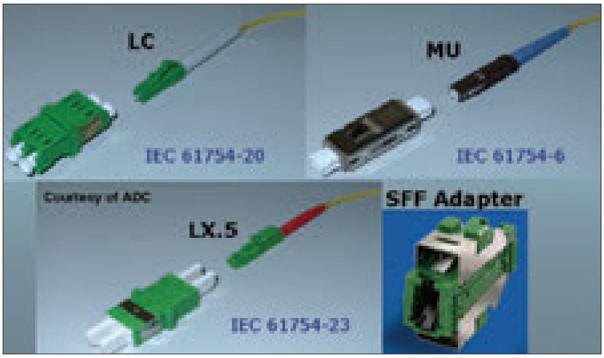


Figure 3.16 – Various small-form-factor connectors with their corresponding IEC performance standards

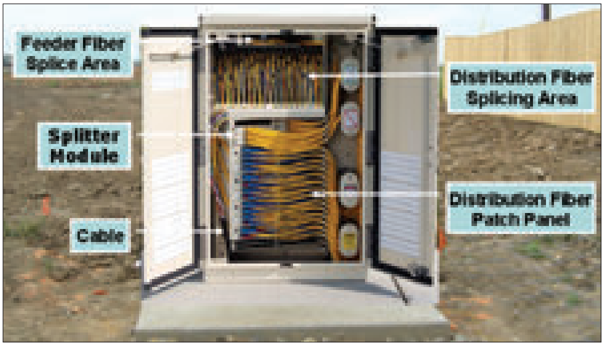


Figure 3.17 – A typical splitter enclosure

Figure 3.18 – Various splitter enclosures

3.4 Fiber and Related Issues

The optical fiber cable is another key component of a PON (P2P and P2MP). The general critical issues related to a fiber can be divided into two categories, as follows[1]:

- Optical
  - Absorption/attenuation
  - Chromatic dispersion and polarization mode dispersion (CD and PMD)
  - Non-linear effects
- Mechanical
  - Bending
  - Connection/joint

3.4.1 Optical Issues

The fiber of choice for PONs is the singlemode dispersion unshifted fiber, based on ITU-T Recommendation G.652 (see Table 3.9) or IEC 60793-2-50 Ed 2. Figure 3.19 illustrates the typical geometry of this fiber type.

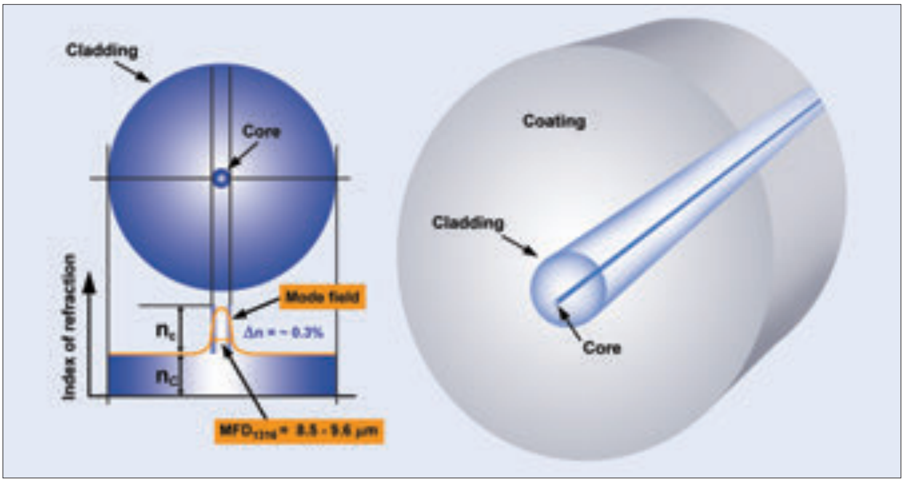


Figure 3.19 – Typical geometry of singlemode dispersion unshifted fiber used in PON

Table 3.9 -- Attenuation characteristics of ITU-T Rec. G.652 singlemode optical fiber (A, B, C and D Categories) and link

Attribute	Range	Specifications			
		A	B	C	D
α (dB/km)	1260 -1360 nm	0.5 (Link)			
	1310 nm; Max.	0.5	0.4		
	1530 -1565 nm	0.275 (Link)			
	1550 nm; Max.	0.4	0.35	0.3	
	1565 -1625 nm	0.35 (Link)			
	1625 nm; Max.		0.4		
	1310 -1625 nm; Max.			0.4	
	1383 ± 3 nm; Max.			≤1310 value after H_2 ageing	

Figure 3.20 shows the spectral attenuation and chromatic dispersion (CD) of the G.652 fiber. Two types of fibers are available for PON, depending on whether or not the 1383 nm water peak is present. It is important to note that there are no CD and PMD impairments for PONs (CD may be an issue only when FP lasers are used at very high bit rate).

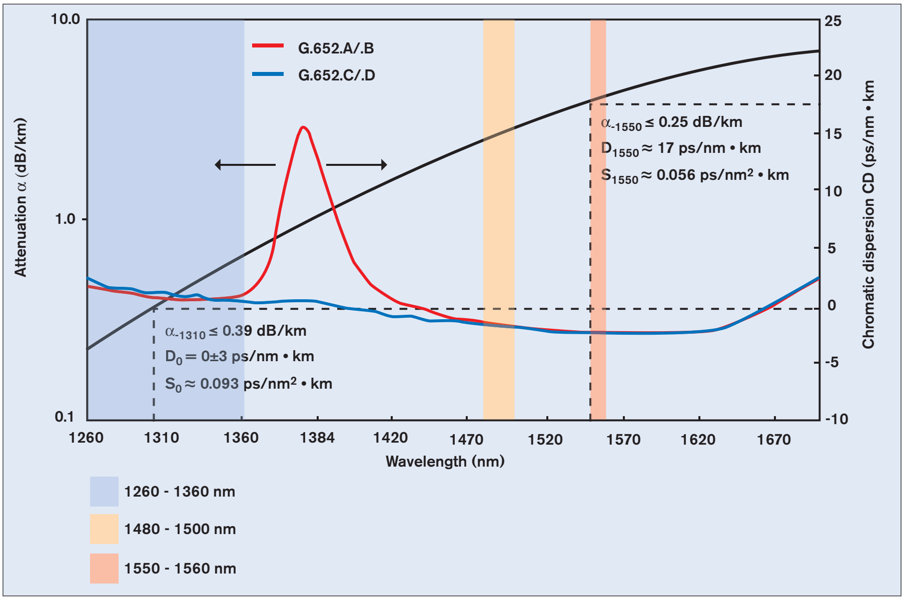


Figure 3.20 – Typical chromatic dispersion and spectral attenuation of FTTH PON fiber

The table below shows CD and PMD performance parameters required for ITU-T Recommendation G.652 fiber.

Table 3.10 – Chromatic (CD) and polarization mode (PMD dispersion characteristics of ITU-T Rec. G.652 singlemode optical fiber (A, B, C and D Categories)

Attribute	Parameter	Specifications			
		A	B	C	D
CD	λ_{0min} (nm)	1300			
	λ_{0max} (nm)	1324			
	S_{0min} (ps/nm^2 • km)	0.093			
	D (ps/nm • km)	+17 (1550)			
	S (ps/nm^2 • km)	0.056 (1550)			
Cabled Fiber PMD	Nob. of cables, M	20			
	Q(%)	0.01			
	Max PMD_Q(ps/√km)	0.5	0.2	0.5	0.2

λ_0 = Zero - dispersion wavelength
S_0 = CD slope at zero dispersion
D = CD value
S = CD sope at stated wavelength

[1] *For further reading on fiber characteristics and test methods, see Girard A., Measuring Fiber Characteristics, Encyclopedia of Modern Optics, Ed. Robert D. Guenther, Duncan G. Steel and Leopold Bayvel, Elsevier, Oxford, pp. 449-467, 2004. ISBN 0-12-227600-0 (www.elsevierphysics.com/emo).*

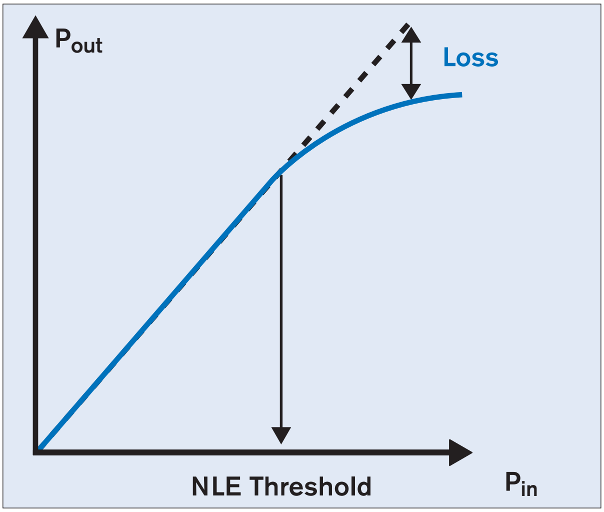


Figure 3.21 -- Power loss due to non-linear effects in a singlemode fiber

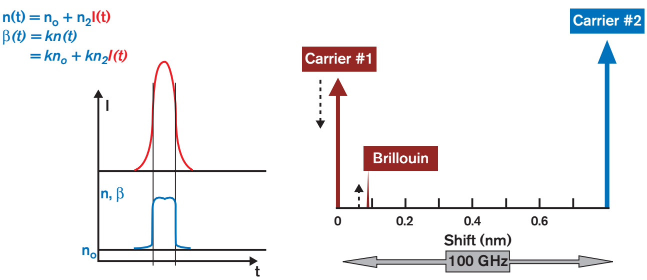
Non-linear effects (NLEs) can be a problem in fiber-optic cables in PONs using high-power video signals at 1550 nm. They are due to changes in the fiber's dielectric properties (index of refraction) or stimulated scattering when using a very high electric field; i.e., the higher the optical power levels (at constant surface area), the higher the electric field. However, when a certain input intensity is reached, the output intensity will follow a non-linear curve, thus no longer increasing linearly. This particular input intensity is called the non-linearity threshold; an example of the non-linear activity is shown in Figure 3.21. The field intensity for a given power level is greater with a smaller fiber core, and longer fiber lengths decrease the threshold for NLE.

Table 3.11 shows how NLEs affect PONs. The most detrimental effect comes from the Brillouin stimulated scattering, which is due to the very high power used in overlaid analog video transmission. Digital IP video should dramatically decrease this effect.

Table 3.11 – General non-linear effects and how they affect PONs

Phenomenon	Name	Nature	Applicability	Remarks
Index of refraction	SPM	1λ	Maybe	At 1550nm
	XPM	Nλ		WWDM
	4WM	Nλ		WWDM
Stimulated scattering	Brillouin	$1\lambda_i$ to $1\lambda_j$	Expected	At 1550nm Backscattering
	Raman	1λ to BB		From 1550 to 1600

SPM = Self-phase modulation
XPM = Cross-phase modulation
4WM = Four-wave mixing
BB = broadband



Index- and phase-related phenomenon *Stimulated scattering-related phenomenon*

Figure 3.22 – Two different non-linear phenomena

3.4.2 Mechanical Issues

As for mechanical aspects, they too can potentially affect the performance of a PON, The following is a list of common mechanical issues to be aware of:

- Bending
  - macrobending
  - microbending
- Discontinuities/gaps/voids
- Misalignments/mismatches
- Cracks/angular or straight breaks
- Dirt in connections
- Fiber melt/fusion splicing

Macrobending (or simply bending) refers to excessive fiber curvature that causes loss of light (see Figure 3.23). When the fiber is bent too much, the angle of total internal reflection between the fiber core and the cladding is no longer met; and since the angle of total internal reflection is what ensures the effective propagation of light inside the core, macrobending can be a major issue as it will reduce the optical energy of the signal. Longer wavelengths (such as 1625 nm and 1650 nm) are more sensitive to macrobending than shorter wavelengths are.

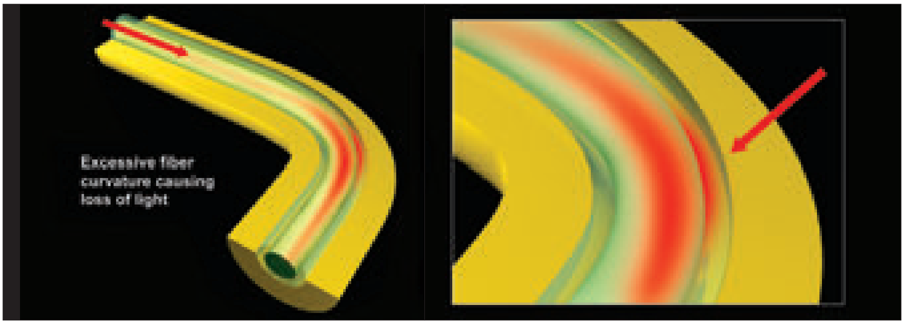


Figure 3.23 – Macrobending in optical fiber

Microbending, on the other hand, is a microscopic bend or bump in the fiber core (shown in Figure 3.24) and is a possible cause of polarization mode dispersion (PMD) in optical fiber.

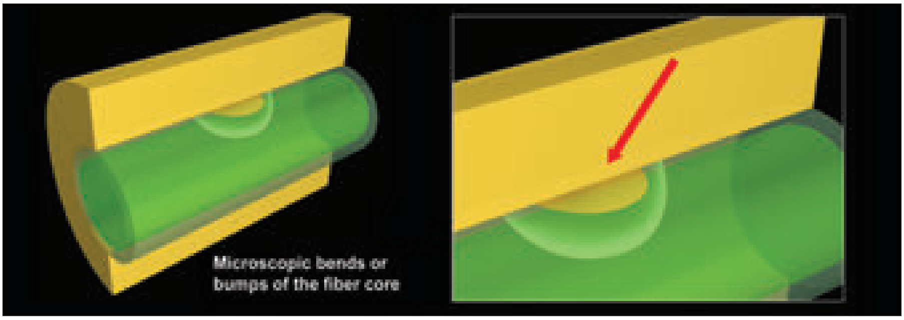


Figure 3.24 – Microbending in optical fiber

Other causes of disruptions include discontinuities, gaps, voids, misalignments, mismatches, angular faults, cracks and dirt (examples shown in Figure 3.25 to Figure 3.28), and they typically occur during the connection of two fibers.

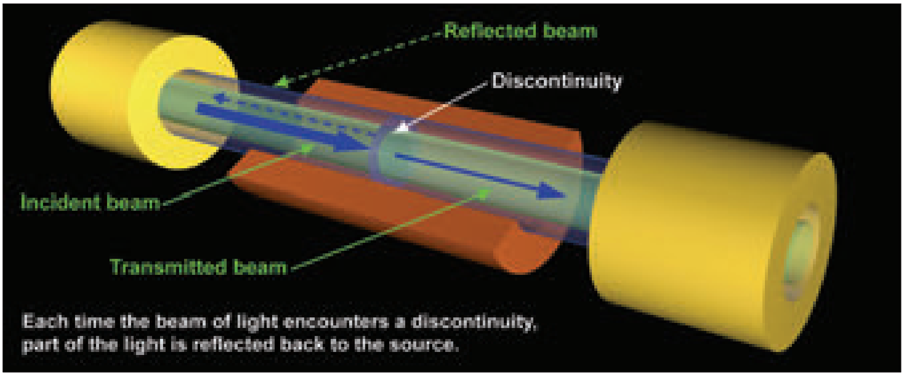


Figure 3.25 – Discontinuities, gaps or voids when connecting two fibers

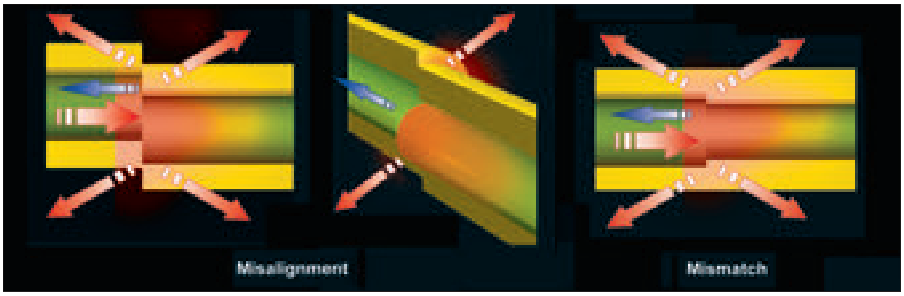


Figure 3.26 – Misalignments and mismatches occurring when connecting two fibers

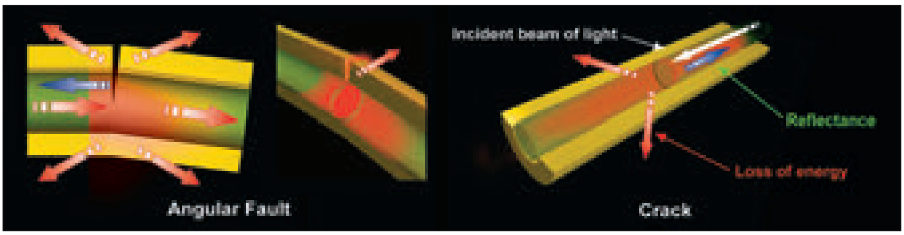


Figure 3.27 – Angular fault and crack when connecting two fibers

All of the above cases can affect the signal traveling through an optical fiber and they mostly occur when human intervention is required (e.g., when joining a fiber).

In addition, if extremely high optical power is used localized laser heating may occur and potentially generate a thermal shockwave back to source. At ~1 m/s the wave produce effects

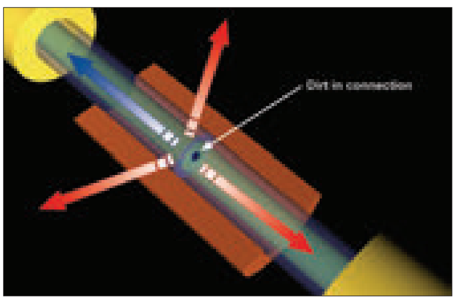


Figure 3.28 -- Power loss due to non-linear effects in a singlemode fiber

balanced between thermal diffusion and light absorption: thermal lensing caused by the periodic bubbling effect in the fused region (as shown in Figure 3.29). Local fiber fusion has been observed at power levels from 0.5 to 3 MW/cm^2.

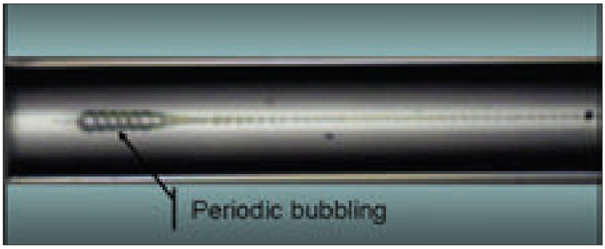


Figure 3.29 – Periodic bubbling in fiber core due to fusion splicing

Courtesy of Draka Comteq

Figure 3.30 – Example of a possible feeder cable design

3.4.3 Fiber Cable Types Used in P2MP PONs

There are three types of cable used in the P2MP PON:

(a) Feeder Cable (from the CO to the splitter distribution hub)

The feeder cable usually has a loose-tube (all-dielectric) design and is the recommended cable type for most PON applications (armor cable is recommended if the cable is directly buried). Figure 3.29 illustrates a possible feeder cable design.

The ANSI/ICEA[2] S-87-640-1999, Fiber-Optic Outside Plant Communications Cable standard defines the requirements for a general-purpose outdoor cable for both the feeder and the distribution cables.

(b) Distribution Cable (from the splitter to the drop enclosures). The distribution cable typically follows the specifications defined for the feeder cable, even though it supports fewer fibers per cable. The distribution cable maybe a ribbon fiber type.

(c) Drop Cable (from the drop enclosures to the premises, see Figure 3.30)

TIA Sub-Committee FO-4.2 Optical Fibers and Cables, has designated ICEA S-110-717-2003, Optical Drop Cables standard as the drop cable specification suitable for FTTP (TIA 472F000).

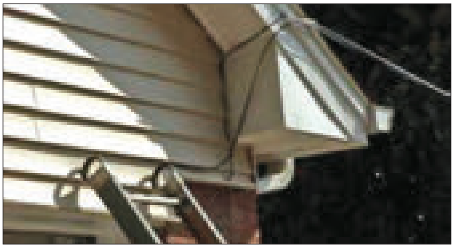
3.5 PON Protocols

3.5.1 Overview

PON architectures are defined in ITU-T recommendations and in IEEE standards; the ITU-T has standardized BPON and GPON, while the IEEE has standardized EPON. One of the main differences between these architectures are the protocols they use for transmission:

[2]*The American National Standards Institute (ANSI) (www.ansi.org) is a private, US-based, non-profit organization that administers and coordinates the US voluntary standardization and conformity assessment system. The Insulated Cable Engineers Association (ICEA) (www.icea.net) is a professional organization dedicated to developing cable standards for the electric power, control, and telecommunications industries.*

Figure 3.31 – a) PON drop cable with possible design



(b) Drop cable installed at the premises

- BPON, defined in ITU-T Recommendation G.983.x series, transports any type of data (voice, video, IP data, etc.) by using ATM protocol, regardless of the type of data link frame.
- GPON, defined in ITU-T Recommendation G.984.x series, transports any type of data by using ATM and GPON encapsulation method (GEM). GEM encapsulates data over GPON and provides connection-oriented communication as well as ATM. At the sublayer level, GPON transmission convergence (GTC) framing is part of the GPON transmission convergence (TC) layer that recognizes the framing and delineation of each data portion.
- EPON, defined in IEEE 802.3ah-2004, uses a multipoint (media access) control protocol (MPCP).

3.5.2 Broadband PON (BPON)

Broadband PON (BPON) is based on the initial PON specifications defined by the FSAN consortium and ratified in the ITU-T G.983 series of recommendations. In 2003, the Joint Procurement Consortium of BellSouth, Verizon, and SBC endorsed BPON, making it a clear leader among PON technologies in the US. BPON uses asynchronous transfer mode (ATM) as the data transport and signaling protocol and allows for analog video overlay on the 1550 nm wavelength. The following sections provide information on the ATM protocol as used in BPON.

3.5.2.1 ATM Protocol

ATM was developed under the ITU-T to support multiservice environments in multitransmission schemes such as continuous, delayed and bursty bit streams. It is the world's most widely deployed backbone technology, within the core and at the access/edge of telecom systems as it can be easily integrated with other technologies and includes management features to guarantee quality of service (QoS). In October of 1991, the ATM Forum started with four computer and telecommunication vendors. ATM Forum membership is made up of network equipment providers, semiconductor manufacturers, service providers, carriers, and end users. The Forum is a consortium of companies that writes specifications to accelerate the deployment of ATM technology through rapid convergence on interoperability specifications and promotion of industry cooperation.

Table 3.12 summarizes the time progress for ATM development. Table 3.13 provides a list of ITU-T recommendations that apply to ATM. These recommendations can be ordered on the ITU-T website at www.itu.int.

Table 3.12 – Timeline for ATM development

Time Period	Event
1984	Development of ITU-T ATM related Recommendations
1984-1988	ITU-T Recommendations on: ▪ Transmission ▪ Switching ▪ Signaling ▪ Control ▪ Support fiber-optic broadband integrated services digital network (B-ISDN)
1991	ATM Forum starts its activities
1996	Migration to multi-service networks
1998	Selection of ATM into PON related ITU-T Recommendation G.983.1

Table 3.13 – List of ATM-related ITU-T recommendations

Rec.	Title
I.113	Vocabulary of terms for broadband aspects of ISDN
I.150	B-ISDN asynchronous transfer mode functional characteristics
I.211	B-ISDN service aspects
I.311	B-ISDN general network aspects
I.321	B-ISDN protocol reference model and application
I.326	Functional architecture of transport networks based on ATM (1995)
I.327	B-ISDN functional architecture
I.356	B-ISDN ATM cell transfer performance
I.361	B-ISDN ATM layer specification
I.363	B-ISDN ATM adaptation layer (AAL) specification
I.364	Support of broadband connectionless data service on B-ISDN
I.365.1	Frame relay service specific convergence sublayer (FR-SSCS)
I.365.2	Service specific co-ordination function to provide CONS
I.365.3	Service specific co-ordination function to provide COTS
I.371	Traffic control and congestion control in B-ISDN
I.413	B-ISDN user-network interface
I.430	Basic user-network interface – layer 1 specification
I.432.1	B-ISDN UNI – physical layer specification general aspects
I.432.2	B-ISDN UNI – physical layer specification 155 520 kbit/s and 622 080 kbit/s
I.432.3	B-ISDN UNI – physical layer specification 1544 kbit/s and 2048 kbit/s
I.432.4	B-ISDN UNI – physical layer specification 51840 kbit/s
I.555	Frame relay bearer service interworking
I.580	General arrangements for internetworking between B-ISDN and 64 kbit/s based on ISDN
I.610	B-ISDN operation and maintenance principles and functions
I.732	Functional characteristics of ATM equipment (1996)

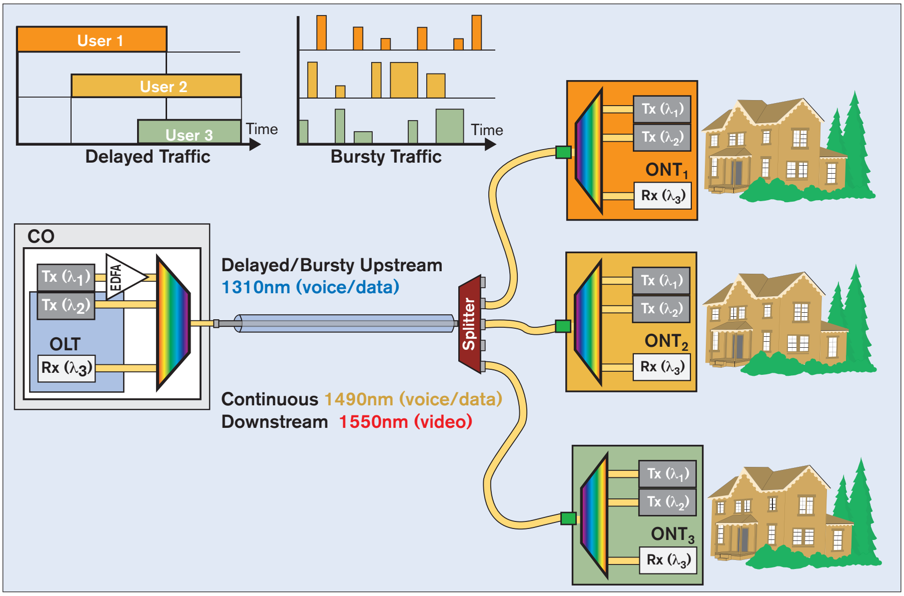


Figure 3.32 – Downstream and upstream traffic types

ATM is a cell-relay technology in that it uses fixed-length cells that are sent on-demand over a lower-level bit stream (see Figure 3.32). In the downstream PON traffic, this low-level bit stream is continuous. In the upstream direction, it is bursty or delayed. ATM is called asynchronous because the cell recurrence is not necessarily periodic (synchronous), even with a continuous bit stream.

To prevent data collisions from different ONT upstream signals arriving at the P2MP PON splitter at the same time, time-division multiple access (TDMA) is used as a transmission technique involving the multiplexing of many time slots onto the same time payload. TDMA allows burst data to be sent from each ONT back to the OLT, at a specific time.

Each ONT transmission time slot is granted by the OLT to a specific ONT so that the packets from various ONTs do not collide with each other. In order to transmit an upstream cell without cell collision in the system, ranging is used to measure the logical distance between each ONT and OLT. Each ONT is assigned a “grant” number, with the lowest number corresponding to the closest distance. The OLT uses this information when deciding when each ONT will be granted permission to send data.

On the switching side, ATM is supported by an intelligent switching fabric and provides fast traffic-switching (all forms) for:

- Voice
- Data
- Images/video
- Multimedia

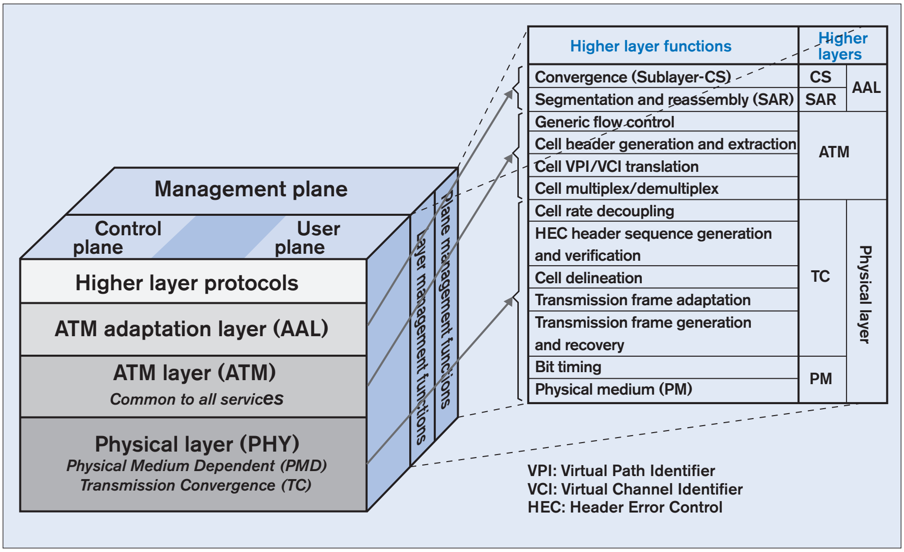


Figure 3.33 – The layer-based structure of the ATM protocol (ITU-T Rec. 1.371)

The bandwidth usage is optimized through application bandwidth-sharing and dynamic bandwidth allocation (DBA), also called dynamic bandwidth assignment.

ATM is based on a virtual circuit (VC) concept in which there are virtual channel connections (VCC). A VCC request implies a signal going from a source to a destination. Upon the destination agreement, the VCC is set up between the source and destination for all communications. Mapping is defined between the user network interface (UNI) virtual channel identifiers (VCIs) and virtual path identifiers (VPIs).

(a) ATM layers

ATM is a layer-based protocol, as illustrated by Figure 3.33

The physical medium-dependent (PMD) layer provides modulation schemes for both upstream and downstream channels. The transmission convergence (TC) layer is responsible for managing the distributed access to the upstream PON resources across the multiple ONTs. This is a key protocol element and directly affects the ATM QoS.

The ATM adaptation layer (AAL) interfaces the higher-layer protocols to the ATM layer. When relaying data from the higher layers to the ATM layer, the AAL segments the data into cells with a 48-byte payload and a 5-byte header for a total of 53 bytes. When relaying data from the ATM layer to the higher layers, the AAL removes the headers and reassembles the data. This is called segmentation and reassembly (SAR).

Figure 3.34 illustrates the ATM protocol transmission from/to a service provider to/from a service subscriber.

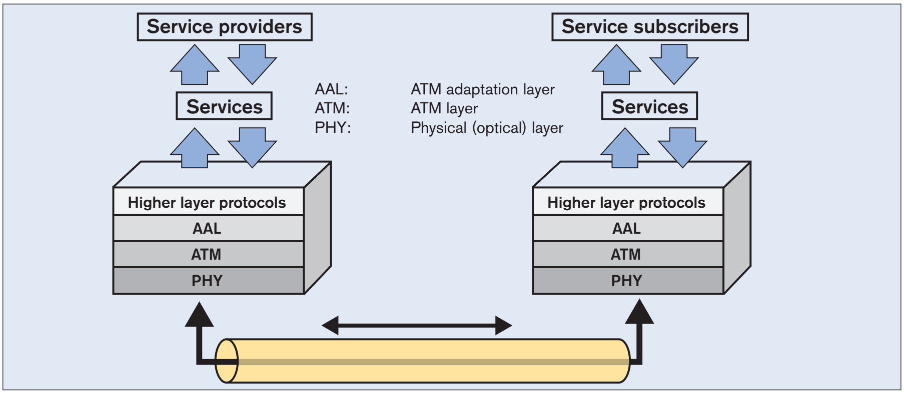


Figure 3.34 – Architecture ATM protocol service transmission structure

Table 3.14 – Transmission medium layer (PHY)

Physical Layer		Specifications in Rec. I.732 and I.326
TC	Adaptation	In Rec. I.732 and I.432.1
	PON Transmission	Ranging in Rec. G.983.1 and G.983.4 MAC Cell slot allocation (statistical bandwidth and DBA) Detection or traffic load for DBA Bandwidth (BW) allocation (service-level agreement and BW request) Privacy and security Frame alignment Burst synchronization Bit/byte synchronization
PMD		Electrical/optical adaptation WDM Fiber connection

The physical layer (PHY) performs functions necessary for PON transmission and converts the signal to the appropriate electrical/optical (E/O) format (see Table 3.14).

(b) ATM adaptation layer (AAL)

Different AALs are defined for supporting different types of traffic or services. ATM has five AALs, numbered AAL1 to AAL5, plus AAL0. The different types of traffic/services are classified as follows:

- Constant bit rate (CBR) service: AAL1 supports a connection-oriented service in which the bit rate is constant. This can be used for voice, uncompressed video and leased lines for private data networks.
- Variable bit rate (VBR) service: AAL2 supports a connection-oriented service in which the bit rate is variable but requires a bounded delay for delivery. This can be used for compressed voice or video signals (packets).

- Connection-oriented data service: Used for data network applications in which a connection is set up before data is transferred, this type of service has a variable bit rate and does not require bounded delay for delivery. AAL3/4 and AAL5 support this class of service.
- Connectionless data service: This type of service is used for data network applications in which a connection is not set up before data is transferred. AAL3/4 and AAL5 support this class of service.

The following is a description of the different AALs:

AAL0: AAL0 cells are sometimes referred to as raw cells. The payload consists of 48 bytes and has no special meaning.

AAL1: AAL1 is used for constant bit rate (CBR) time-dependent traffic (voice, and video uncompressed video and leased lines for private data networks). This corresponds to:

- A static amount of bandwidth
- Real-time, tight transfer delay
- Downstream PON voice and video traffic

The AAL1 protocol data unit (PDU) structure is shown in Table 3.19.

Table 3.15 – AAL1 protocol data unit (PDU) structure

<table>
<tr><th colspan="2">Sequence Number (SN)</th><th colspan="2">Sequence Number Protection (SNP)</th><th rowspan="3">Segmentation and reassembly (SAR) PDU user information payload</th></tr>
<tr><td>Convergence sublayer indicator (C SI)</td><td>Sequence count (SC)</td><td>Cyclic redundancy check (CRC)</td><td>Even parity check (EPC)</td></tr>
<tr><td>1 bit</td><td>3 bits</td><td>3 bits</td><td>1 bit</td></tr>
<tr><td colspan="4">1-byte Header Convergence Sublayer (CS)</td><td>47 bytes</td></tr>
<tr><td colspan="5">AAL1 48-byte protocol data unit (PDU)</td></tr>
</table>

AAL2: AAL2 provides bandwidth-efficient transmission of low-rate, short and variable packets in delay-sensitive applications. It supports a connection-oriented service with a variable or constant bit rate (VBR or CBR) and provides variable payload within cells and across cells. AAL2 requires a bounded delay for delivery. This can be used for compressed voice or video signals (packets).

AAL2 is used for real-time VBR (RT-VBR) timing-sensitive traffic. This corresponds to:

- Source-destination timing + bit rate variation with time
- Downstream PON voice traffic

AAL2 convergence sublayer (CS) is subdivided into the common-part convergence sublayer (CPCS) and the service-specific convergence sublayer (SSCS).

An AAL2 CPCS packet consists of a three-byte header followed by a payload.

Table 3.16 – AAL2 protocol data unit (PDU) structure (common-part convergence sublayer)

Sequence Number (SN)		Sequence Number Protection (SNP)		
Channel identification (CID)	Sequence Length indicator (LI)[1]	User-to-user indication (UUI)[2]	Header rrror control (HEC)	Information payload
8 bits	6 bits	5 bits	5 bits	
3-byte Header Convergence Sublayer (CS)				45 bytes
AAL2 48-byte protocol data unit (PDU) (CPCS or SSCS)				

[1]Associated with each individual user
[2]Link between CPS and appropriate SSCS satisfying higher layer application

The AAL2 CPCS packet structure is shown in Table 3.16.

AAL2 SSCS packets transport narrowband cells consisting of voice, voice-band data or circuit mode data. SSCS packets are transported as CPCS packets over AAL2 connections. There are three SSCS packet types:

- Unprotected (used by default)
- Partially protected
- Fully protected with the entire payload protected by 10-bit cyclic redundancy check (CRC) computed as for operation and maintenance (OAM) cells. The remaining 2 bits of the 2-byte trailer consists of message-type field.

AAL3/4: AAL3/4 was originally two AAL types, connection-oriented and connectionless, which have since been combined for data service. This is for data network applications where a connection is set up before data is transferred. This type of service has a variable bit rate and does not require bounded delay for delivery. AAL3/4 consists of message and streaming modes. It provides point-to-point and point-to-multipoint (ATM layer) connections. The AAL3/4 CS is divided into the following two parts:

- Service-specific convergence sublayer (SSCS)
- Common-part convergence sublayer (CPCS)

The functions of the AAL3/4 CS PDU include:

- Connectionless network layer, meaning there is no need for an SSCS
- Frame relaying telecommunication service

AAL3/4 is consequently used for non-real-time (bursty) VBR (Burst-VBR) delay-tolerant data traffic. This AAL:

- Requires sequencing and/or error detection support
- Combines AAL connection-oriented and connectionless types
- Is used for upstream PON data traffic

The AAL3/4 PDU structure is shown in Table 3.17.

Table 3.17 – AAL3/4 protocol data unit (PDU) structure

Header	Information			Trailer			
Common part indicator (CPI)	Beginning tag (Btag)	Buffer allocation size (BAsize)	Variable information field (CPCS SDU)	Padding field (Pad)	All-zero	End tag (Etag)	Length (same as BAsize)
1	1	2	0-65535	0-3	1	1	2
Byte number							

AAL5: AAL5 is a simplified version of AAL3/4. It consists of message and streaming modes, and is divided into the service-specific and common–part CS. AAL5 provides point-to-point and point-to-multipoint connections.

AAL5 is used for VBR, delay-tolerant connection-oriented data traffic and to carry computer data such as TCP/IP. It is the most popular AAL and is sometimes referred to as SEAL (simple and easy adaptation layer) AAL5:

- Requires minimal sequencing or error-detection support
- Is a simple and efficient AAL for available bit rate (ABR) and unspecified bit rate (UBR)
- Is used for upstream PON data traffic

AAL5 PDU structure is shown in Table 3.18.

Table 3.18 – AAL5 protocol data unit (PDU) structure

Information	Trailer				
CPCS payload (actual information sentby the user)	Padding field (Pad)	CPCS user-to-user indication to transfer one byte of user information	Common part indicator (CPI) (a filling byte of value 0)	Length of the user information without the Pad	CRC - 32 bits (Used to allow identification of corrupted transmission)
0-65535	0-47	1	1	2	4
Byte number					

Table 3.19 -- ATM AAL service application

Applications	AAL1	AAL2	AAL3/4	AAL5
	CBR	RT-VBR/VBR/ CBR	Burst-VBR	VBR/ABR/UBR
	Voice and Video	Downstream Voice	Data	Upstream Data
PON Traffic Direction	Downstream		Upstream data	
POTS/ISDN	1			
Circuit Emulation-PBX		2		
Computer Process Swapping/Paging				1
Data Transport (IP/FR)	3		1	2
Distance Learning 1				
Distributed Files Services				1
E-mails				
Interactive Multimedia	1		2	
LAN	3		2	1
Large File/Data Transfer/Back-Up			1	
Messaging/Telecommuting				1
MP3	3	1	2	
MPEG				
Remote Procedure Calls				1
Transactions (Airlines/Banks/Defense/Security)			1	2
Video Distribution (TV/VOD/PPV/Teleconferencing	1			

ABR: available bit rate
CBR: constant bit-rate
RT-VBR: real-time variable bit-rate
UBR: unspecified bit rate
"1" means the best fit for the indicated service, "2" means second-best fit, etc.

Table 3.19 summarizes the ATM application service capability as it applies to PONs.

3.5.2.2 Data transmission

Physically speaking, the transmission is based on the ATM cell sequence frame in the downstream direction and on the timeslot frame in the upstream direction. When the cell goes downstream, the OLT sends ATM cells or physical-layer operation, administration and maintenance (PLOAM) cells. The ATM cells contain the information payload to provide to the ONTs. The downstream PLOAM cells are control cells that grant transmission permission to the ONTs. When the cell goes upstream, the transmission is made of ATM frame timeslots, each consisting of overhead and either an ATM cell or a PLOAM cell.

The cells are short, fixed-length packets of information. Each downstream cell is 53 bytes long or 424 bits. Of the 53 bytes, 5 bytes are reserved for a header field and 48 bytes are used for information payload. The header field consists of the following:

- Virtual channel identifier (VCI)
- Virtual path identifier (VPI)
- Payload type (PT)
- Cell loss priority (CLP)
- Header error control (HEC)

Together, VCI and VPI make up the virtual-path channel identifier (VPCI) and represent the routing information within the ATM cell. The 48 remaining bytes (384 bits) are used for the payload, defined as the information field.

The ATM frames, cells, bytes and bits are transmitted in the following order referring to their numbering:

- Frames are transmitted in ascending order
- Cells within a frame are transmitted in ascending order
- Bytes within a cell are transmitted in ascending order
- The most significant bit (MSB) is transmitted first within one byte
  - The MSB is bit number 1
  - The least significant bit (LSB) is bit number 8 (for example the LSB of 010101010 is equal to 1).

The upstream timeslot has a 3-byte overhead plus the 53-byte ATM or PLOAM cell content. 53 time slots are sent at a time in the upstream frame transmission.

To provide a certain amount of data protection ATM applies a function to the downstream user data from an OLT to its ONTs. This function is called churning. Churning provides data scrambling and offers a low level of protection for data confidentiality. Churning protection is installed at the TC layer and can be activated for P2P downstream connections. BPON security and protection have since been improved (ITU-T Rec. G.983.2 Rev. 2, G.983.5, and G.983.6).

(c) Downstream transmission

In order for the OLTs to control the upstream transmission and avoid collision between messages from different ONTs and establish message priority, a physical-layer operation, administration and maintenance (PLOAM) cell is used by the PON ATM protocol. In the downstream direction, one PLOAM cell is inserted after every 27 ATM cells.

Figure 3.34 illustrates the structure of the downstream ATM cell and the PLOAM cell. The PLOAM cell contains 27 permission grants with a cyclic redundancy check (CRC) every 7 grants to ensure protection and efficiency. A grant is a one-time permission from the OLT to an ONT to transmit subscriber's payload data in the upstream direction.

Each ATM cell contains:

- Information payload
- Signaling
- OAM
- Unassigned byte
- Cell rate decoupling

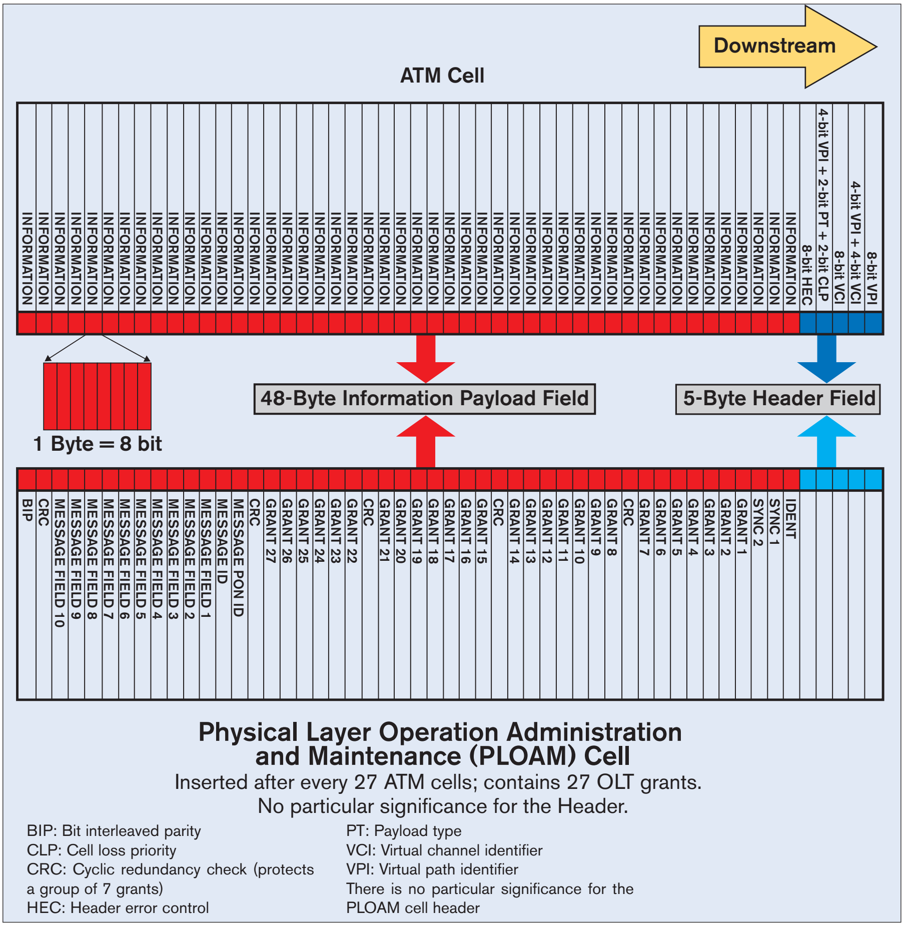


Figure 3.34 – BPON downstream ATM and PLOAM cells structures

Each PLOAM cell:

- Conveys the PLOAM
- Carries permission grants provided by the OLT to the ONTs allowing them to transmit one upstream cell in a determined and indicated upstream timeslot per ONT (depending on bandwidth service-level agreement (SLA) between the service provider and the subscriber).

Table 3.20 illustrates granting structure.

Table 3.20 – Grant structure in ATM PON

Bit Rate (Mb/s)		PLOAM Cells	Total Grants	Idled Grants
Downstream	Upstream			
155.52	155.52	2	53	Last one
622.08	155.52	8	53	Last one of 2nd PLOAM cell + Last 6 cells
622.08	622.08	8	212	Last one of every 2 PLOAM cells
1244.16	155.52	16	53	Last one of 2nd PLOAM cell + Last 14 cells
1244.16	622.08	16	212	Last one of every 2 PLOAM cells for the first 8 cells + Last 8 cells

Figure 3.35 illustrates the downstream ATM frame and the PLOAM insertion.

Figure 3.36 shows how the downstream transmission is divided between a number of ONTs.

Cells transmitted to any subscriber are broadcast simultaneously to all

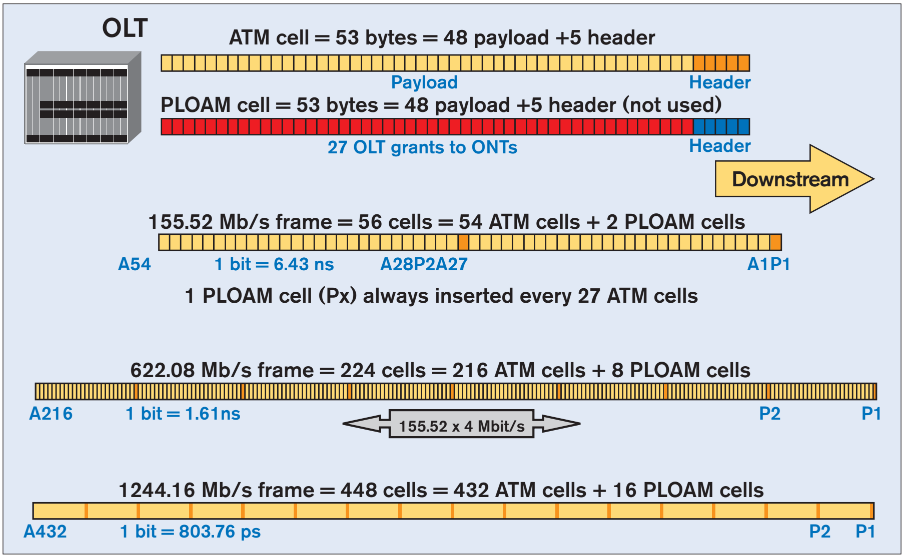


Figure 3.35 – BPON downstream ATM frame with PLOAM insertion

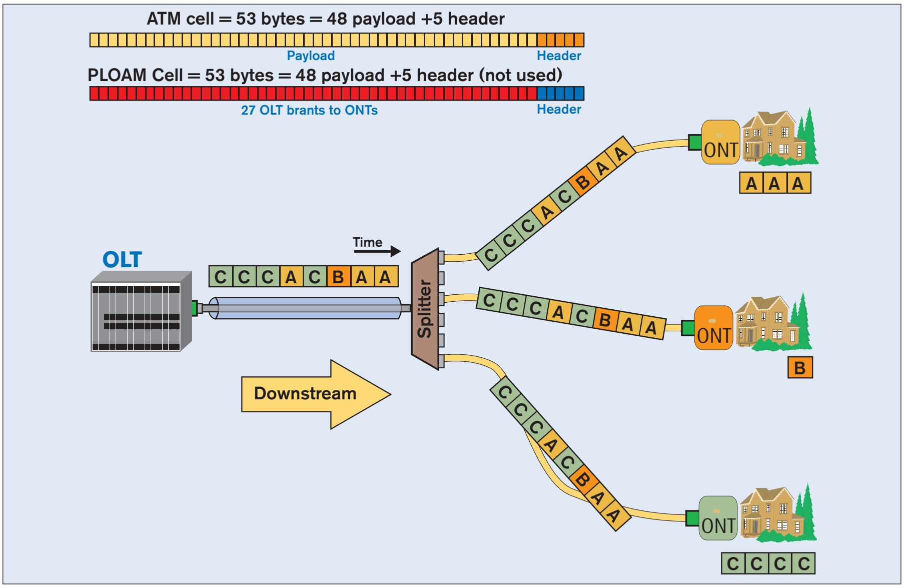


Figure 3.36 -- Downstream transmission

subscribers on the PON. Addressing information in each cell indicates the intended recipient, and each ONT blocks data that is not addressed to it.

(d) Upstream transmission and dynamic bandwidth allocation (DBA)

The upstream transmission is controlled by the OLT, which defines (through the granting process) a number of timeslots for the ONTs to transmit. There are 53 timeslots per basic ATM frame and each timeslot has 53 bytes, plus a 5-byte overhead. The 53 timeslot bytes can be an upstream ATM cell or an upstream PLOAM cell. The timeslot structure and the various bit-rate frames are shown in Figure 3.37, while Figure 3.38 illustrates the detailed byte structure of the timeslot.

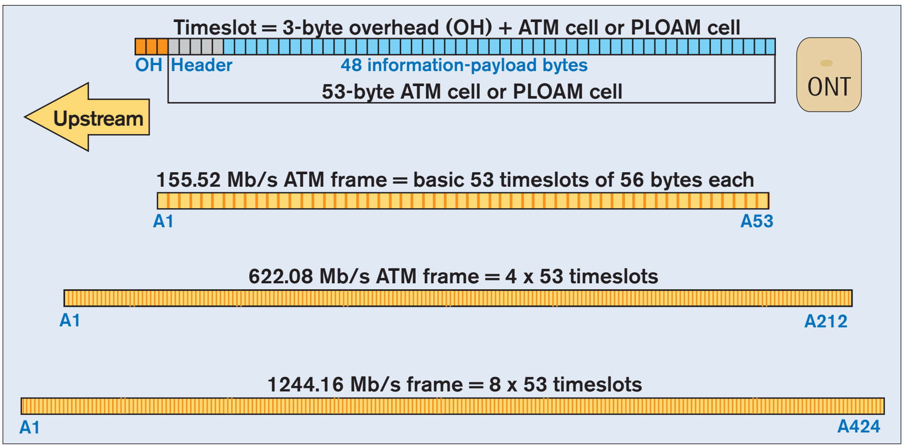
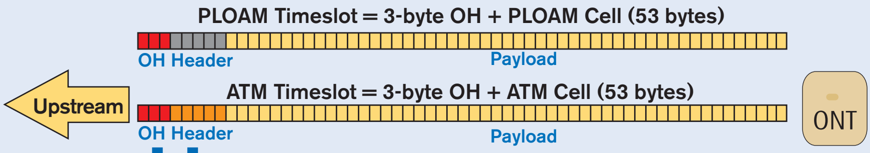


Figure 3.37 – Upstream transmission



5-Byte Header	
Byte No.	**Content**
1	8-bit VPI
2	4-bit VPI +4-bit VCI
3	8-bit VCI
4	4-bit VPI + 2-bit PT + 2-bit CLP
5	8-bit HEC

VPI = Virtual Path Identifier
VCI = Virtual Channel Identifier
PT = Payload Type
CLP = Cell Loss Priority
HEC = Header Error Control

3-Byte OLT Programmable Overhead		
Byte No.	Field	Content
1	Guard time	Delay (minimum 4 bits) between two consecutive cells for avoiding collision
2	Preamble	Extract the phase of the arriving cell relative to the OLT local timing and/or Acquire bit synchronization and amplitude recovery
3	Delimiter	Unique pattern indicating the start of ATM cell Can be used for byte synchronization

Figure 3.38 – Detailed timeslot byte structure

In the upstream direction, the physical-layer overhead includes:

- PLOAM cells (media access control (MAC) channel mini-slots) for transferring the status of the ONTs queues to the OLT, in order for it to properly manage and control the bandwidth allocation. An illustration of upstream PLOAM is shown in Figure 3.39.
- Overhead bytes in front of each upstream cell.

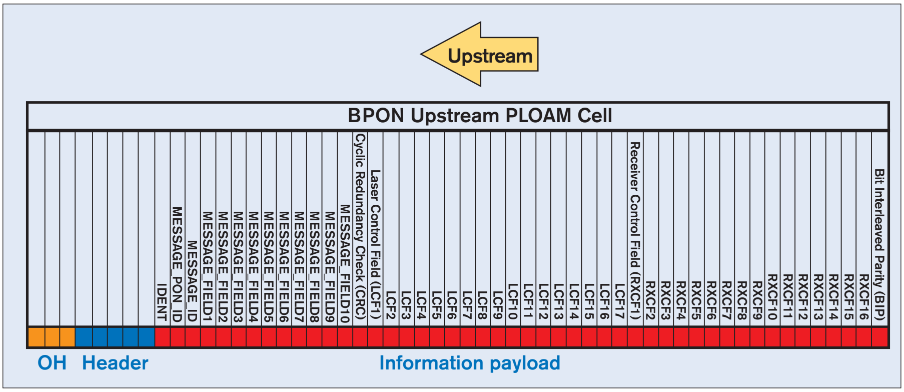


Figure 3.39 – Upstream PLOAM cell

(e) Dynamic bandwidth assignment (DBA)

The static bandwidth control in BPON is not a particularly efficient process for bursty or delayed traffic, though it is very much applicable to constant-bit-rate traffic. A dynamic bandwidth assignment (allocation) (DBA) process has been defined by FSAN and ITU-T Recommendations G.983.4 and G.983.7 to set different levels of priority and facilitate the management of BPON bandwidth. This allows flexible support of a wide range of services with appropriate levels of QoS. Figure 3.40 illustrates a static bandwidth management (SBA) compared to a DBA management.

The global BPON bandwidth capacity can be divided into four different types of bandwidth, ranging from best-effort to fixed, each having its own level of priority depending on the service-level agreement (SLA) between the service provider and the service subscriber, as shown in Table 3.2. The fixed bandwidth is allocated cyclically and is well suited to SBA. The other types of bandwidth are assigned dynamically, by the DBA function, distributed among different ONTs and among the different traffic flows from each ONT. The use of DBA results in improved QoS and more efficient use of PON bandwidth. If needed, more ONTs can be allowed to transmit or more bandwidth may be allocated to a particular ONT, as shown in Figure 3.40.

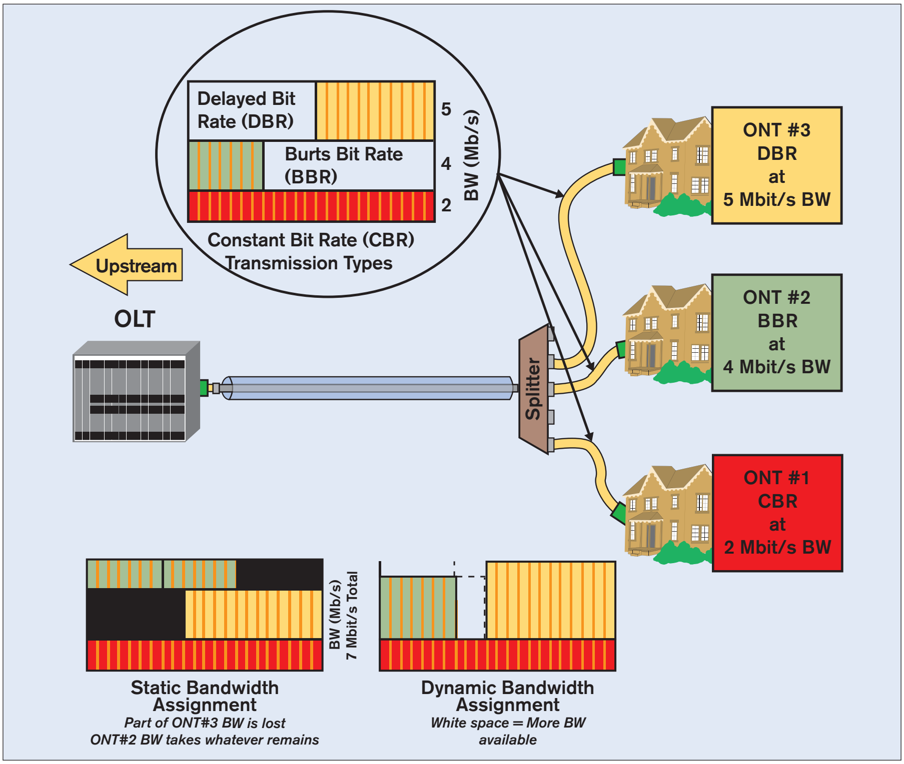


Figure 3.40 – Dynamic bandwidth assignment (DBA) compared to static bandwidth assignment (SBA)

Table 3.21 – DBA priority levels

Priority	Bandwidth	
Lowest	**Best Effort** Dynamically allocated when available	**Additional**
	Non-Assured Dynamically allocated in proportion to assured bandwidth, when available	
	Assured Guaranteed to be available Can be dynamically reallocated if not used	**Guaranteed**
Highest	**Fixed** Guaranteed reserved whether used or not	

3.5.3 Gigabit PON (GPON)

A further evolution of PON technology is Gigabit PON (GPON), defined by the ITU-T G.984 series of recommendations. GPON is optimized on the physical layer to support higher data rates, greater distances, and higher split ratios than other PON technologies. GPON reuses many G.983.x concepts such as DBA, protection, ranging, PLOAM messaging, etc., and offers robust support for OAM and QoS. As shown in Table 3 on page 21, GPON can support up to seven different combinations of symmetric and asymmetric downstream/upstream data rates up to a symmetric 2.5 Gb/s.

GPON offers full service support, including voice, Ethernet, ATM, leased lines, wireless extension, etc., by using either ATM or GPON encapsulation method (GEM), or both (dual or mixed mode). GEM is a method which encapsulates data over GPON. It is generic in that any packet-based service can be transported using GEM, including Ethernet and native time-division multiplexing (TDM) services. The actual encapsulation types depend on the service. The concept and framing format are similar to generic framing procedure (GFP), a framing and encapsulated method used with SONET/SDH.

With GEM, the variable-length Ethernet frames are not transmitted natively but are fragmented. This allows the use of fixed, periodic framing so that services with very strict requirements can be serviced and transported at the right moment. Although Ethernet frames must be reassembled after reception, GPON transports Ethernet more efficiently than EPON as it has much lower overhead. GPON supports IP video over Ethernet or ATM and offers standardized support for analog video overlay. Table 3.22 shows the main differences between GPON and EPON. EPON is covered in detail in Section 3.5.3.

Table 3.22 -- Main Differences between GPON and EPON

<table>
<tr><th colspan="3"></th><th colspan="2">GPON</th><th colspan="2">EPON</th></tr>
<tr><td rowspan="4">MAC Layer 2</td><td rowspan="3" colspan="2">Frame</td><td colspan="2">Ethernet over GEM</td><td rowspan="3" colspan="2"></td></tr>
<tr><td colspan="2">ATM over GEM</td></tr>
<tr><td colspan="2">Ethernet/ATM over GEM</td></tr>
<tr><td colspan="2">TDM Support</td><td colspan="2">TDM over GEM</td><td colspan="2">TDM over Packets</td></tr>
<tr><td rowspan="15">PHY Layer 1</td><td rowspan="3" colspan="2">Distance (km)</td><td colspan="4">10</td></tr>
<tr><td colspan="4">20</td></tr>
<tr><td colspan="2">Logical: 60</td><td colspan="2"></td></tr>
<tr><td rowspan="3" colspan="2">Split ratio</td><td colspan="2"></td><td colspan="2">16</td></tr>
<tr><td colspan="4">32 / EPON with FEC or DFB/APD</td></tr>
<tr><td colspan="2">64 / 128
Logical and limited by IL</td><td colspan="2"></td></tr>
<tr><td rowspan="5">Bit rate (Mbit/s)</td><td></td><td>Downstream</td><td>Upstream</td><td>Downstream</td><td>Upstream</td></tr>
<tr><td>155.52</td><td></td><td>X</td><td rowspan="2" colspan="2"></td></tr>
<tr><td>622.08</td><td></td><td>X</td></tr>
<tr><td>1244.16</td><td colspan="2">X</td><td colspan="2">1000 Nominal</td></tr>
<tr><td>2488.32</td><td colspan="2">X</td><td colspan="2"></td></tr>
<tr><td colspan="2">Line Coding</td><td colspan="2">NRZ + Scrambling</td><td colspan="2">8B/10B data stream</td></tr>
<tr><td rowspan="3" colspan="2">Loss Budget (dB)</td><td colspan="4">15</td></tr>
<tr><td colspan="4">20</td></tr>
<tr><td colspan="2">25</td><td colspan="2"></td></tr>
</table>

Chapter 3

In that sense, GPON offers more bandwidth capabilities and much more flexibility than BPON and EPON. It is also a better system for supporting video services than BPON and EPON. Consequently, it appears to be more cost-effective then BPON and EPON. However, the decision for selecting one PON architecture over another should also be weighted according to the targeted applications, the market, and the operating environment.

Table 3.23 shows how ATM, GEM, TDM and Ethernet are transported with GPON.

Table 3.23 -- GPON protocol transport

	OLT				
	ATM	GEM	DUAL	TDM	Ethernet
OLT	X	X	X	Directly mapped over GEM (TC Layer)	
ONT	X	X			

GEM	Defined in fixed block lengths (default length = 48 bytes)
	Negotiated by GPON ONT Management Control Interface (OMCI)

OLT = Optical Line Terminal
ONT = Optical Network Terminal
ATM = Asynchronous Transfer Mode
GEM= GPON Encapsulated Method
TDM = Time Division Multiplexing
TC = Transmission Convergence

GEM uses fixed block lengths with a default length of 48 bytes (the same BPON ATM payload length). Transmission is negotiated by the ONT management and control interface (OMCI). The GPON element managing system (EMS) manages ONTs using the OMCI. The OMCI allows the OLT to make and release connections to ONTs, manage UNIs, detect link failures, etc.

3.5.3.1 GPON TC Frame Structure

The following figures show the GPON frame structure for downstream and upstream transmission. Each upstream and downstream frame has a fixed duration of 125 μs. The number of bytes in the frame depends on the bit rate. For instance, at 1244.16 Mb/s downstream, the total number of available bytes is 19440, while at 2488.32 Mb/s, the numbers increases to 38880. The downstream frame consists of a data information payload and a physical control block (PCB) header used for operation, administration and maintenance (OAM), for upstream bandwidth grants allocation and dynamic bandwidth allocations. The length of the PCB though being fixed depends on the number of ONTs to be served. Figure 3.41 shows a downstream GPON frame and an example of a bandwidth grant allocation map showing how this information is used, including a detailed byte distribution of the PCB.

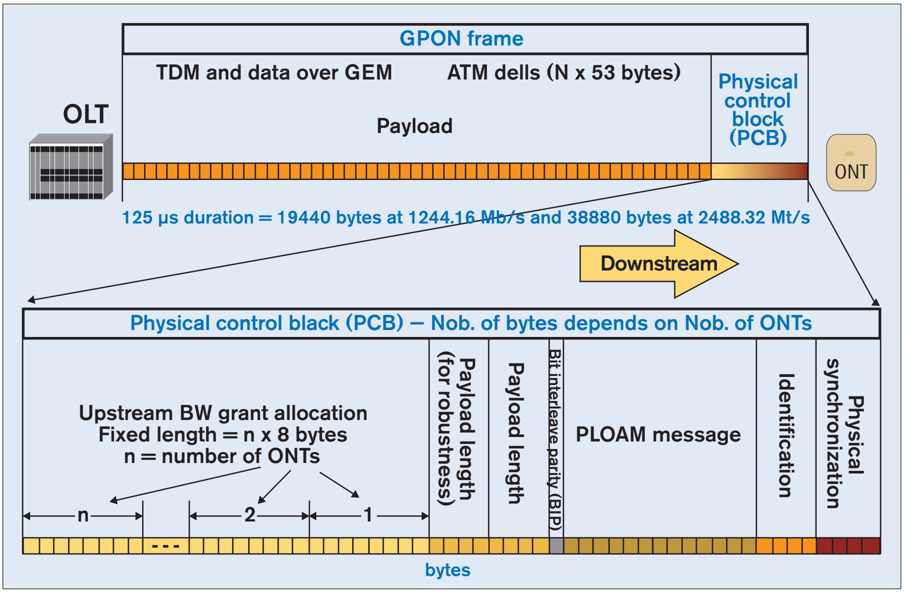


Figure 3.41 – GPON downstream frame and PCB header structure (BW=Bandwidth)

In the PCB, one of the most important subframes is the upstream bandwidth grant allocation, which determines the number of grants for the ONTs, the start time and the end time of each ONT upstream timeslot (called in GPON, the transport container – T-CONT). Essentially, as shown in Figure 3.42, the upstream bandwidth grant allocation is the OLT management of the upstream transmission. The process goes as follows:

- The allocation identification ensures that the particular ONT T-CONT (timeslot) is well identified
- The start and stop bits define the start and the end location of each ONT T-CONT in the overall upstream transmission. The process is illustrated in Figure 3.43
- The flag bits define how the ONT T-CONT allocation will be used (shown in Figure 3.44).

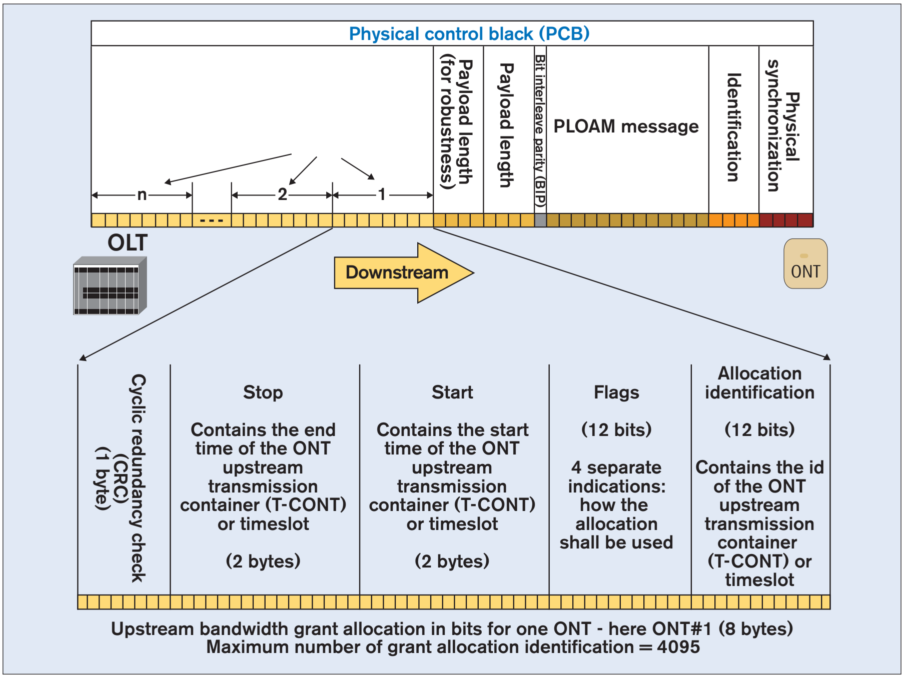


Figure 3.42 – Upstream bandwidth grant allocation block in the downstream physical control block

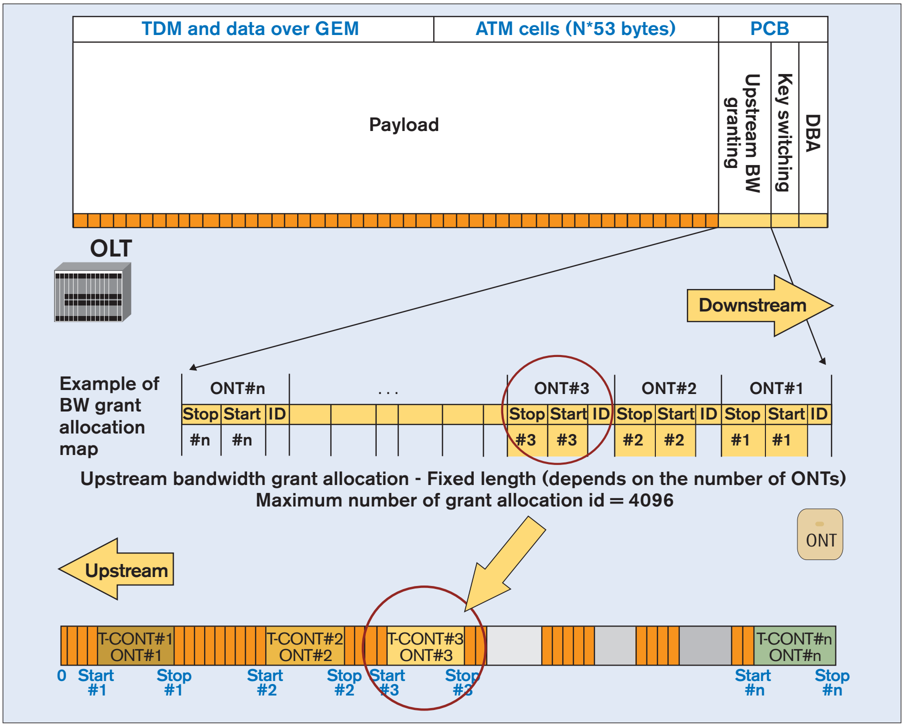


Figure 3.43 – Management of the upstream T-CONT transmission from the downstream physical control block

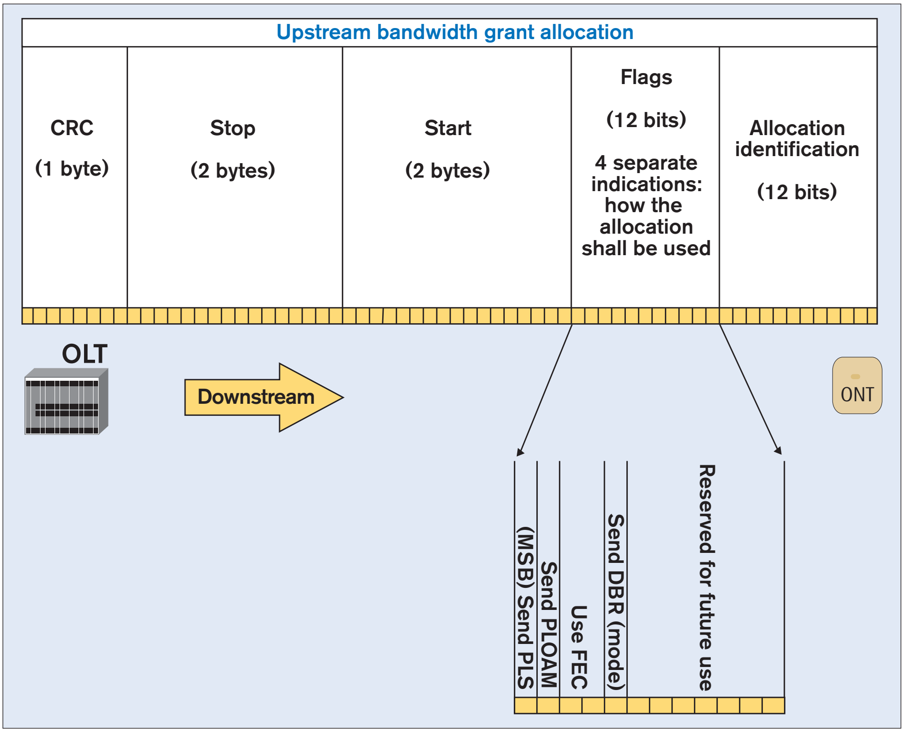


Figure 3.44 – Indication flags in the upstream bandwidth grant allocation block

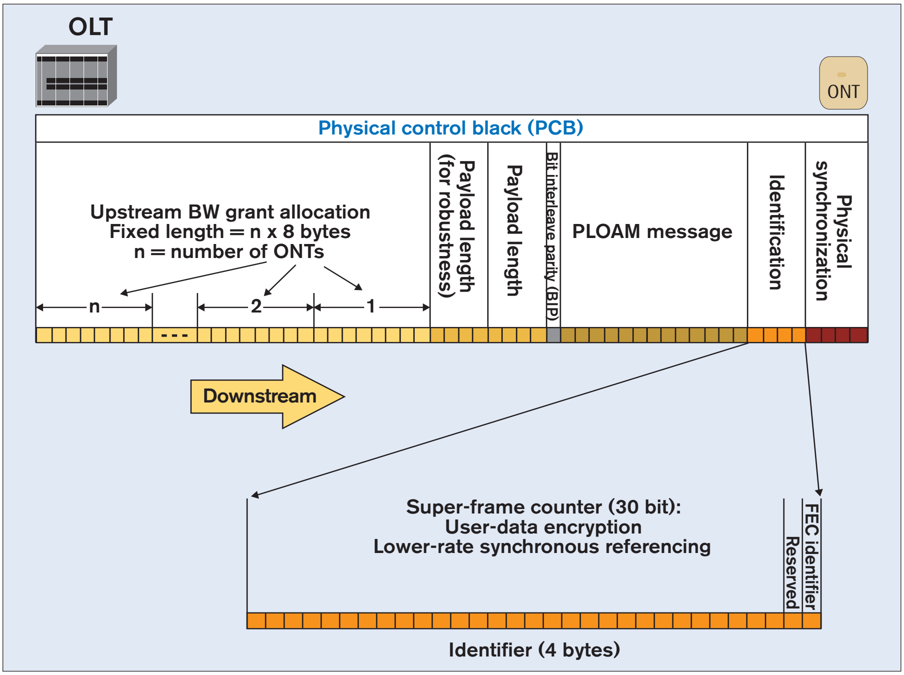


Figure 3.45 – Identification block in the PCB header

There are also two other bit contents in the PCB that are important to the efficient management of the upstream transmission: identification and payload information. The 4-byte identification segment contains a super 30-bit counter (see Figure 3.45) to ensure proper user-data encryption and lower-rate synchronization referencing. The identification also contains one bit for FEC identification.

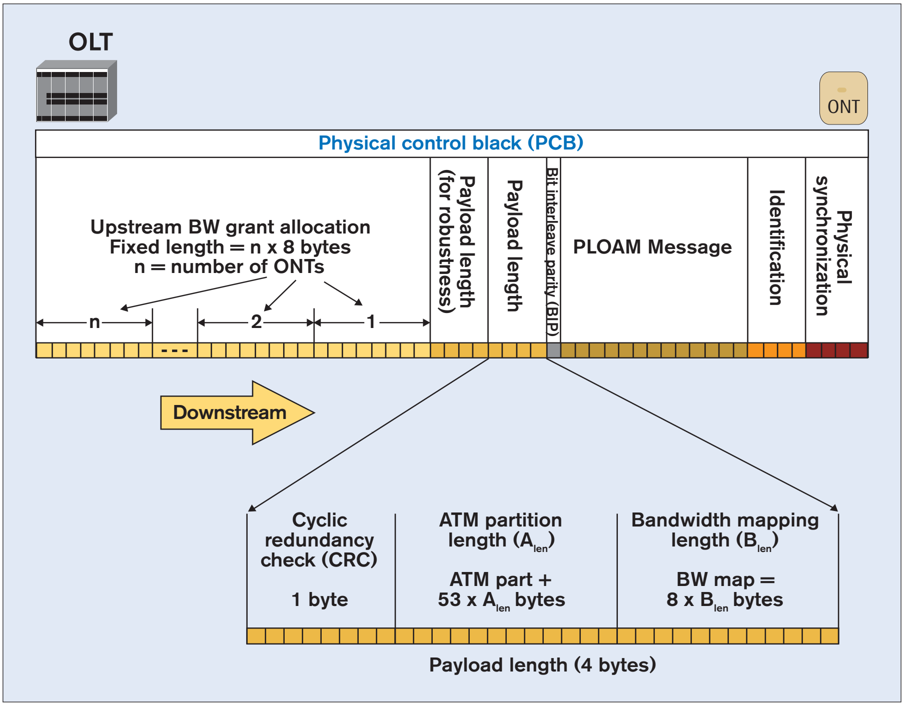


Figure 3.46 – Payload length block in PCB header

3.5.3.2 GPON Protocol and Upstream Traffic Management

The GPON upstream frame is similar to that of the BPON: it contains a number of overhead bytes (three are used in BPON), PLOAM messaging, an ONT laser control, information on dynamic bandwidth assignment and, finally, a data information payload. Figure 3.47 illustrates upstream transmission with GPON, showing the four different types of overhead (OH), as well as the payload for different types of transmissions:

One ONT with one grant allocation **(a)**

One ONT with more than one grant allocation **(b)**

More than one ONT, each with one grant allocation **(c)**

It can be seen from Figure 3.47 (b), that when more than one grant has been provided to the ONT, the physical-layer overhead (PLO), PLOAM and power leveling sequence (PLS) are not repeated for further grant allocations. In fact, for contiguous allocation identifications, only the upstream dynamic bandwidth report (DBR) and payload are used for each grant. When more than one ONT is transmitting, however, a frame must be transmitted for each ONT with its corresponding PLO, PLOAM, PLS, DBR and payload as illustrated in Figure 3.47 (c).

As shown in Figure 3.47 (a) the PLO is the first part of the GPON, followed by the upstream bursts. The PLO contains two bit-rate-dependent fields accommodating five physical-layer processes, and three fixed-byte fields. Figure 3.48 shows the PLO distributed bytes and accommodation processes.

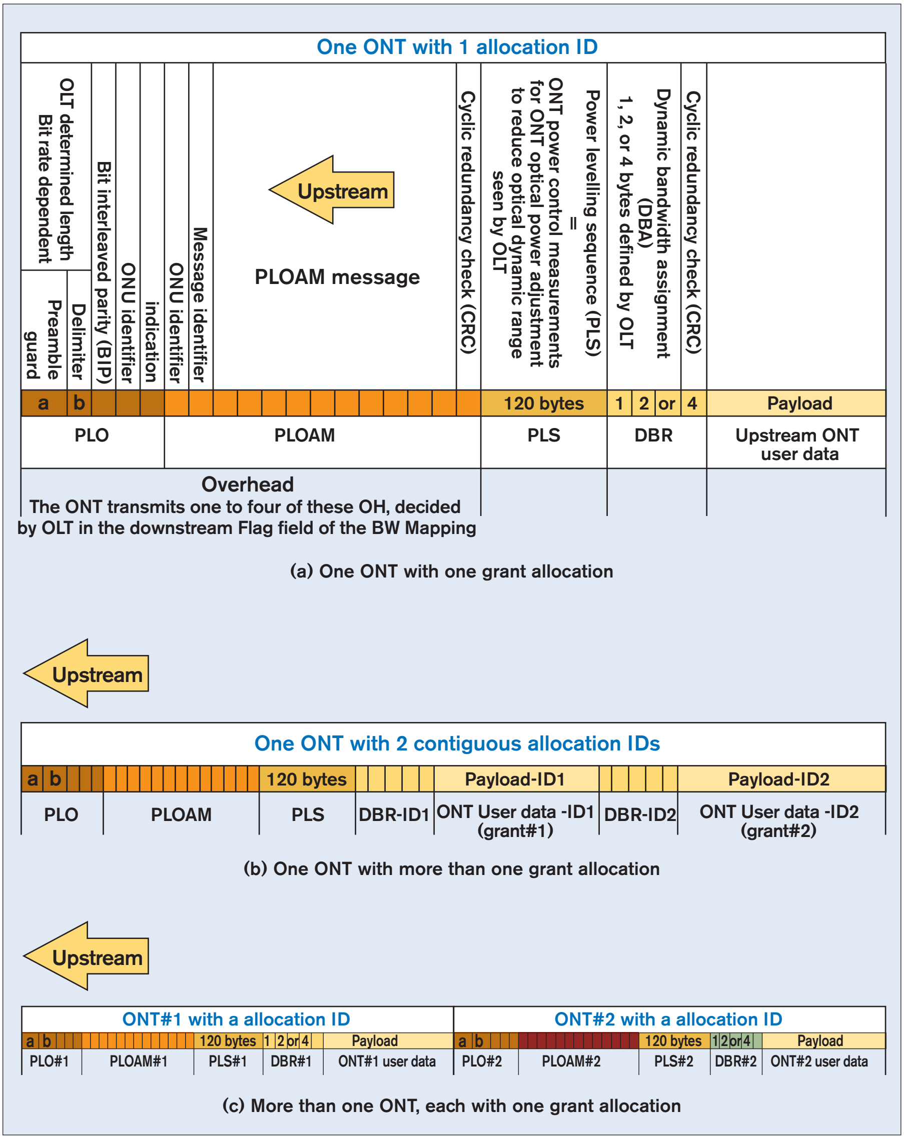


Figure 3.47 -- Upstream transmission

Upstream

Physical Layer Overhead (PLO)				
OLT determined length bit rate dependent		Bit interleaved parity (BIP)	ONU identifier	Indication
Guard/ preamble	Delimiter			
Variable	Variable	1 byte	1 byte	1 byte

5. accomodation process
1. Laser on/off time,
2. Timing drift tolerance
3. Signal level recovery,
4. Clock recovery, and
5. Start of burst delimitation

Upstream data rate	T_g	T_p	T_d	PLO
Mb/s	bits			bytes
155.52	6	10	16	4
622.08	16	28	20	8
1244.16	32	44	20	12
2488.32	64	108	20	24

Same type OH bytes as in upstream BPON cell

Guard time T_g	P_{ONT} = 0 for avoiding collision between 2 consecutive calls
Preamble time T_p	P_{ONT} = preamble pattern providing maximal transition density for fast level and clock recovery functions
Delimiter time T_d	P_{ONT} = special data pattern with optimal autocorrelation properties enabling the OLT to find the beginning of the burst
Uncertainty time variance T_u	Total peak-to-peak timing uncertainty arising from time-of-flightvariations caused by fibre and component environment sensitivity

Figure 3.48 – Detailed byte and process structures of the upstream physical-layer overhead

GPON can accommodate various types of upstream payload:

- ATM
- GEM
  - TDM
  - Ethernet
- DBA reporting

Figure 3.49 to Figure 3.52 show details of the upstream transmission of ATM, GEM and dynamic bandwidth assignment (DBA) report payloads.

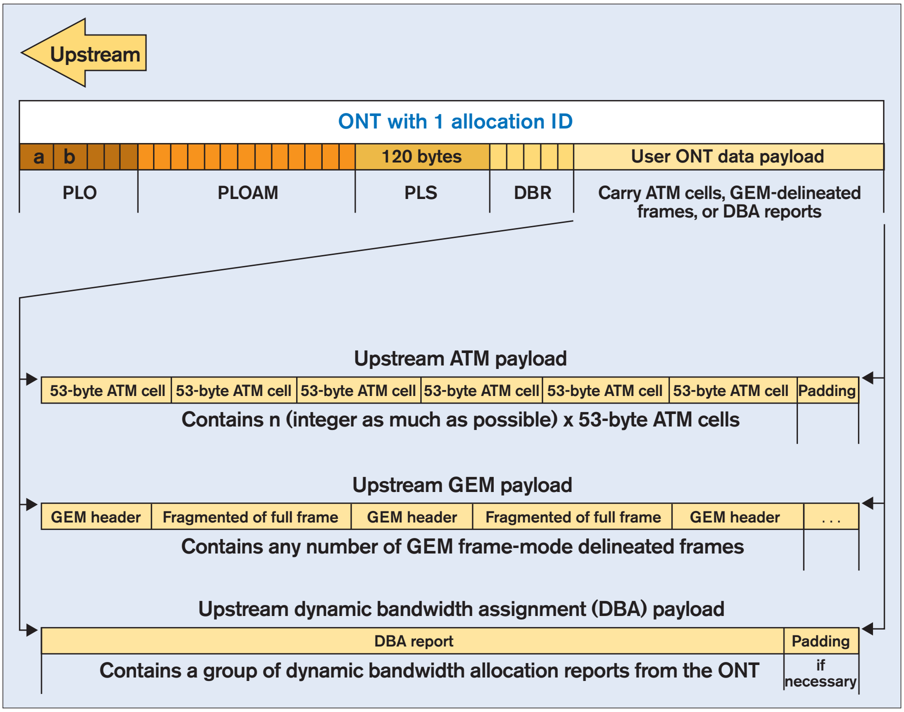


Figure 3.49 – GPON upstream payload types

In the case of an ATM-transmitted payload, the 53-byte ATM cells are used. For GEM, a header and frame are used. Finally, in the case of DBA payload, transmission contains a group of DBA status reports from the ONT.

In the GEM payload, the header contains the following (see Figure 3.33):

- The payload length indicator (PLI), allowing payload fragments up to 4095 bytes
- The port identification field, allowing 4096 unique PON traffic identifiers and PON traffic multiplexing
- The payload type indicator (PTI), providing the payload content type
- A typical header error control (HEC) field

The length of the GEM header is five bytes.

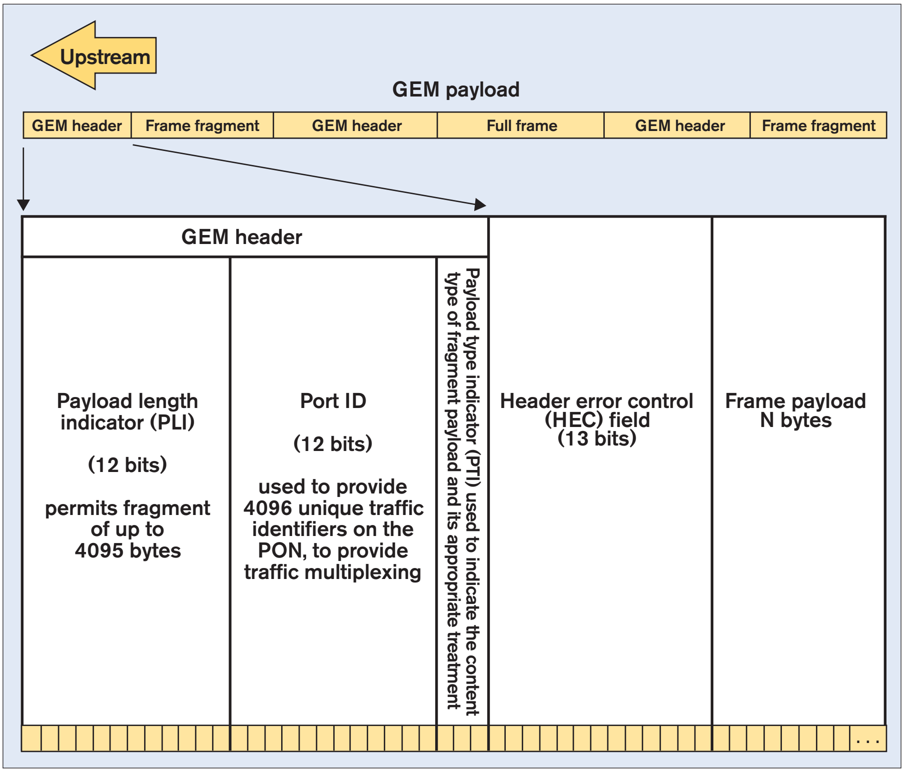


Figure 3.50 -- Upstream GEM payload header

As mentioned above, GPON can transport various types of payload. The DBA report payload may have various lengths depending on the assignment field content. Figure 3.34 illustrates the three formats available for the DBA report payload over GPON.

GEM can also transport both TDM and Ethernet over GPON, demonstrating how GPON is one of the most flexible PONs. Figure 3.52 shows how TDM and Ethernet data packets are mapped over GEM into a variable-length payload.

Finally, in GPON as well as in BPON, the ONT management and control interface (OMCI) is ensured by a specific frame, as shown in Figure 3.53. ATM and GEM OCMI is again mapped to GPON; this time, with a fixed 53-byte (5 bytes of header and 48 bytes of information) format showing the structure of the ONT management and control interface (OMCI) cells.

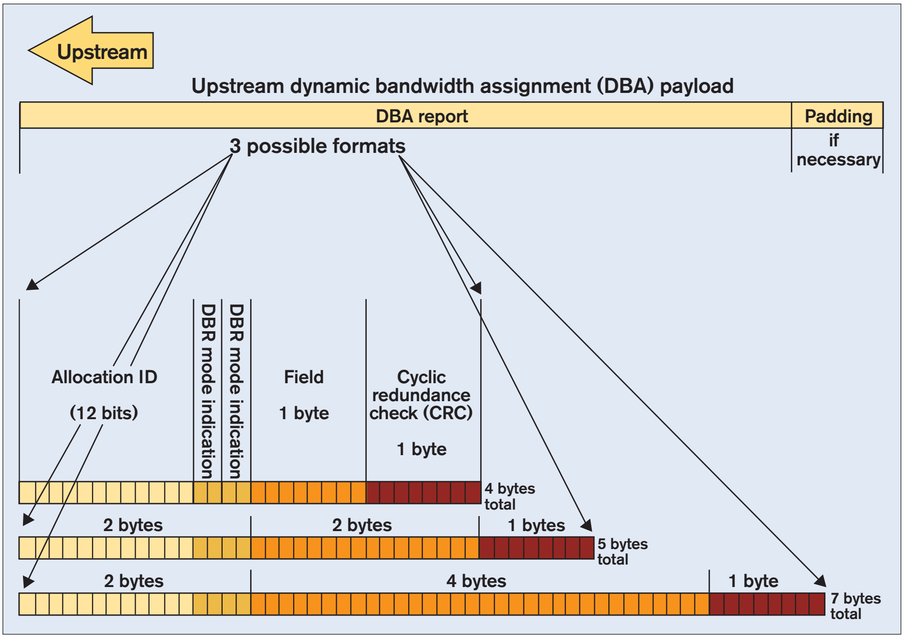


Figure 3.51 -- Upstream DBA payload

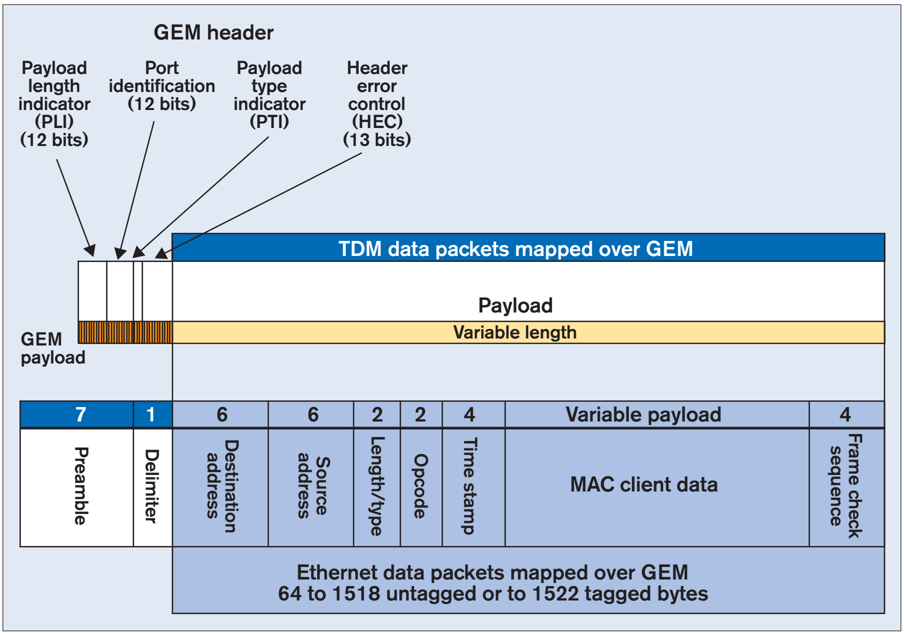


Figure 3.52 -- TDM and Ethernet transmission mapped over GEM

[1]*IEEE 802.3-2002, IEEE Standard for Information technology - Telecommunications and information exchange between systems – Local- and metropolitan-area networks - Specific requirements – Part 3: Carrier-sense multiple access with collision detection (CSMA/CD) access method and physical-layer specifications*

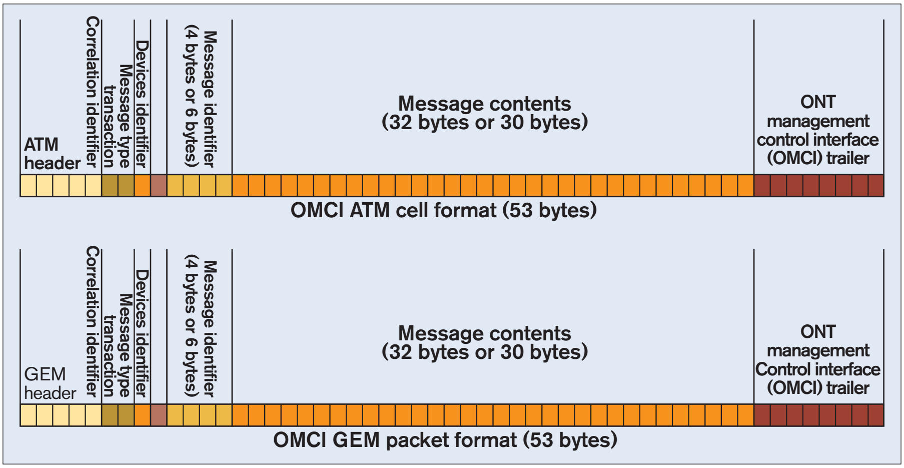


Figure 3.53 -- ONT Management and Control Interface (OMCI)

3.5.4 Ethernet PON (EPON)

This section provides a general view of the Ethernet protocol and how it is applied to the FTTP and FTTH PON.

3.5.4.1 Ethernet Services

Ethernet was born in the 1970s at Xerox. By 1980, the first Ethernet standard was published by Digital Equipment Corporation (DEC), Intel and Xerox. That document finally evolved into the Institute of Electrical and Electronic Engineers or IEEE 802.3[1] standard, published in 1983 and defining an access network transmitting data at 10 Mb/s over 500 m of coaxial cable.

Since then, Ethernet gradually became one of the world's most predominant network protocols, not only in local-area networks (LANs) but, more recently, in metropolitan- and wide-area networks (MAN and WAN) as well (see Figure 3.54). Today, Ethernet is the most widely deployed access technology in carrier networks, and in new installations; Ethernet access lines are outselling all other forms of access combined.

What makes Ethernet so attractive is its capability to either replace, or be used in combination with other transport protocols and infrastructures such as ATM, frame relay, and SONET/SDH.

Recent Ethernet standards, such as Gigabit Ethernet, 10 Gigabit Ethernet, as well as emerging technologies such as the multiprotocol label switching (MPLS) and resilient packet ring (RPR), are helping to make Ethernet a reliable and economically viable carrier-class transport technology.

Ethernet also offers low cost and simplicity, compared to legacy services such as T1/T3[2]. Ethernet has a long history of achieving lower equipment costs than

[2] *T1 = 1.544 Mb/s; T2 = 6.312 Mb/s; T3 = 44.736 Mb/s (telephone hierarchy)*

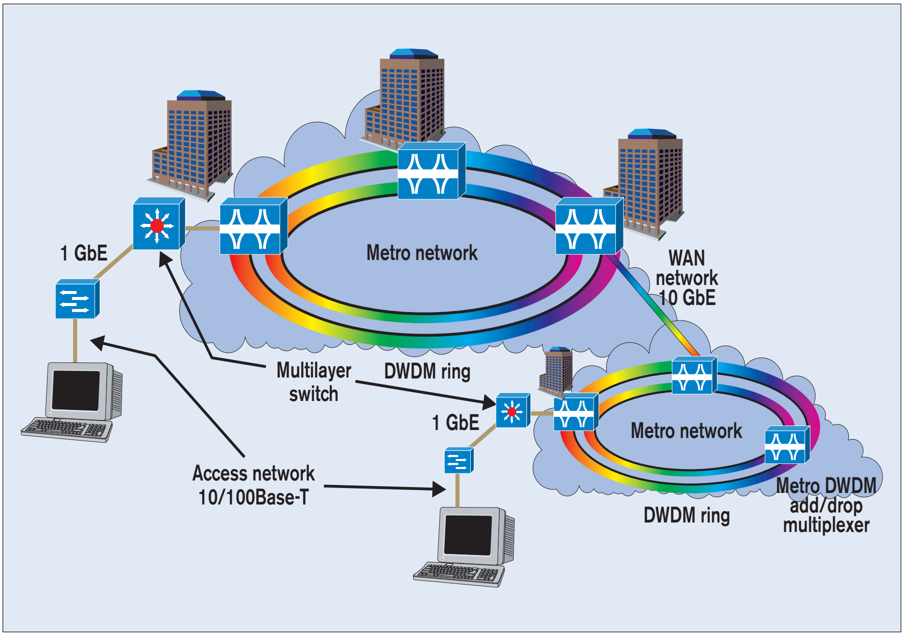


Figure 3.54 -- Ethernet in access networks, MAN and WAN

competing technologies, mostly due to economies of scale. Manufacturers are now offering economic solutions for the following applications:

- Ethernet switching and routing
- Virtual LAN (VLAN) services
- MPLS
- IP forwarding
- Traffic-management features allowing service providers to fulfill various service agreements

Ethernet services require less time for commissioning and provisioning than legacy services and can even be remotely provisioned, resulting in savings for service providers. In addition, since almost all LANs use Ethernet, they can easily be integrated with Ethernet-based carrier networks since Ethernet equipment performs bit-rate conversion and statistical multiplexing.

Ethernet is flexible in that it can be used with many different infrastructures and protocols. Ethernet services can be offered over existing ATM architectures. In next-generation SONET/SDH networks, Ethernet frames can be encapsulated into generic framing procedure (GFP) frames and transported through SONET/SDH channels. Ethernet can also be transmitted in its native format over dark fiber or on a WDM wavelength, or using free-space optics (FSO).

Another aspect of Ethernet's flexibility is that it allows dynamic bandwidth

[3] *IEEE 802.3-2004, IEEE Std 802.3ah.-2004, IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local- and metropolitan-area networks - Specific requirements - Part 3: Carrier-sense multiple access with collision detection (CSMA/CD)*

provisioning, giving enterprise access customers the ability to change their bandwidth by any desired increment when required. For example, a subscriber can temporarily increase Ethernet access from 10 Mb/s to 100 Mb/s when using video conferencing. The change can be made at the subscriber's request or, automatically if the agreement requires incremented bandwidth under certain conditions or for certain periods, such as in the evening or the last week of each month. The subscriber is billed according to the bandwidth provided. By contrast with T1/T3 fractional access, although any number of 64 kb/s channels may be subscribed to, bandwidth changes take time and are expensive to make as they require new hardware and service provisioning. This inflexibility often results in subscribers purchasing bandwidth based on their highest level of usage or oversubscribing to meet growing bandwidth needs.

Ethernet offers a wide scope of access services, such as:

- Ethernet private line
- Ethernet virtual private line
- Virtual private wire service
- Ethernet wire service
- Ethernet relay service
- Ethernet virtual private LAN
- LAN extension service
- Transparent LAN service
- Virtual private LAN service
- Ethernet private LAN

It also offers value-added services including:

- Ethernet Internet access
- Voice-over-Internet protocol (VoIP)
- Video-streaming-over-Ethernet
- Storage-area networks (SANs)

At the IEEE, EPON started to emerge in 1998, but it wasn't until 2001 that work started on the actual standardization of the EPON within the framework of IEEE 802.3ah; this task was undertaken by the Ethernet in the First Mile Alliance (EFMA). Table 3 25 shows the structure of the IEEE technical committee responsible for the development of the IEEE 802.3ah[3] EPON standards.

3.5.4.2 IEEE 802.3ah-2004

The IEEE 802.3ah-2004 Amendment 1[4] defines physical-layer specifications in conjunction with an operation, administration and maintenance (OAM) sublayer for extending the reach and providing monitoring, fault detection and localization in the access network. A fixed speed of 1.25 Gb/s (1000 Mb/s nominal) symmetrical was selected, and the development has taken on a wider scope than originally anticipated. As Ethernet assumes a P2P connection, the new P2MP physical layer must be emulated to appear as a set of

IEEE 802 LAN/MAN Standards Committee			
	802.1	Higher layer protocols	
	802.3	CSMA/CD working group (ethernet)	
		802.3ad	Link aggregation
		802.3ae	10 Gigabit
		802.3ah	*Ethernet in the first mile task force*
			P2P 1GbE P2MP EPON
		802.3z	10GbE
		Etc.	

Table 3.25 -- Breakdown of the IEEE 802 LAN/MAN standards committee

access method and physical-layer specifications, (Amendment to IEEE Std 802.3.-2002 as amended by IEEE Stds 802.3ae -2002, 802.3af.-2002, 802.3aj.-2003 and 802.3ak.-2004)

P2P connections for the higher layers; this is done in the P2P emulation sublayer within the MAC sublayer. EPON uses native Ethernet to run multimedia traffic over multiple channels.

EPON is popular in many parts of the world. In fact, 65% of the global FTTx deployments so far have used P2P Ethernet solutions (either actively switched or passive). Examples of this deployment are the B2 network in Sweden and Fastweb in northern Italy. Ethernet appears as an attractive solution for the overlaid PON when using active Ethernet switches.

The following are reasons why optical Ethernet has been successful in the access networks:

- Point-to-point

To allow for multiple access and collision detection, P2MP topologies have overhead. This is not needed in P2P links. However, a P2P link naturally requires a fiber pair, which is not required in a P2MP link.

- Ethernet switches

The unique MAC addresses in the Ethernet frames enables low-cost L2[5] Ethernet switches to be used rather than routers. L3 switches can also be used for increasing manageability.

- Separation of PMD and media-independent interface (MII)

In the Ethernet standard, the PMD hardware (e.g., receptacles, lasers and detectors together with their electronics) is separated from the MII (e.g., the chip sets handling the Ethernet control logic). This creates flexibility when choosing subcomponents, which can be lower-cost alternatives.

- Optimized for data traffic

Ethernet has been developed on the basis of data traffic load. Ethernet is inexpensive to deploy and maintain, and it is easy to integrate into end-user devices.

- Dominant technology for LAN

The massive deployment of Ethernet LANs made the Ethernet components available in mass volumes. Migration of Ethernet further out into the network continues to drive cost reduction. Emergence of low-cost Gigabit Ethernet cards in business PCs and laptop computers is driving the need for faster Ethernet access links. As Gigabit Ethernet is increasingly used in the enterprise market, 10 Gigabit Ethernet becomes the natural choice for access/metro networks. The 10 Gigabit Ethernet standard is inexpensive to deploy, further enhancing the business case for Ethernet in PON access networks.

3.5.4.3 Ethernet PON Transport Architecture

Figure 3.55 to Figure 3.57 illustrate the topologies supported by IEEE 802.3ah (EFM) and IEEE 802.3 (Gigabit Ethernet). The P2P fiber-pair (Figure 3.55) and

[4]IEEE 802.3ah-2004 amendment 1 "Media access control parameters, physical layers, and management parameters for subscriber access networks" September 7, 2004
[5]The ISO/IEC OSI (Open Systems Interconnection) Reference Model is a 7-layered description

P2MP single-fiber (Figure 3.57) EPON architecture are in fact similar to BPON and GPON, as they have the same type of topology, except that PON only supports P2MP topology. There is a feeder-fiber cable from the CO OLTs (one OLT per fiber pair) to the first distribution hub where a patch panel enclosure will be efficiently located to serve a number of localized premises. From that hub, another cable, this time with much fewer fiber pairs, will run as close as possible to the group of premises. At that location, the drop enclosure will distribute the fiber pairs over a few tens of meters to each premises, where the ONTs will be deployed (see the upper portion of Figure 3.55). From the first distribution hub, the feeder cable and remaining incoming fiber pairs will be fusion-spliced to the remaining outgoing fiber pairs. The cable will be directed to the second distribution hub, where again the hub will be conveniently located to serve a block of other premises. The drop process will be repeated again to the ONT of each premises (see the lower portion of Figure 3.55).

In Figure 3.57, the EPON topology services only one fiber instead of two fibers (a fiber pair). The distribution hub patch panel is thus replaced by a 1 x N splitter sharing the incoming bandwidth among N premises.

The major difference between the EPONs shown here and the network shown in Figure 3.55 is the use of an active network instead of a PON. In the active network, the passive components used in the distribution hub are replaced with an Ethernet digital cross-connect switch (DCS) especially the MPLS switch. A P2P network may require the use of two DCS, one for each fiber in the fiber pair for each premises. The use of a DCS in the hub now completely changes the requirement and the design of the hub enclosure. In the PON, the hub enclosure only offers a protective cover to the passive component (the patch panel or the splitter), while in the active network the hub itself must now offer additional active electrical power source with backup and complete air conditioning system. That makes the life-cycle cost of the active network quite high compared to the PON. However, the active Ethernet network still appears to be a cost-effective and attractive solution in the overlaid topology, where the fiber cables are already deployed and DCS hubs are already available in most cases. Obviously, the major difference then between an active Ethernet access network and other active network technologies is the low-cost and wide-spread Ethernet solution.

The IEEE 802.3ah standard has defined two types of EPON P2MP system architecture: the 1000BASE-PX10 system and the 1000BASE-PX20 system. Their deployment topologies are essentially the same, but their architectures differ. Table 3.26 summarizes their major differences. Essentially, EPON operates at a fixed data rate of 1000 Mb/s nominal; for 1000BASE-PX10, in particular, the split ratio is limited to 1 x 16, while its maximum reach is 10 km.

of how messages should be transmitted between any two points in a telecommunication network. L1 is the physical layer, L2 is the data link layer, L3 is the network layer, L4 is the transfer layer, L5 is the session layer, L6 is the presentation layer and L7 is the application layer.

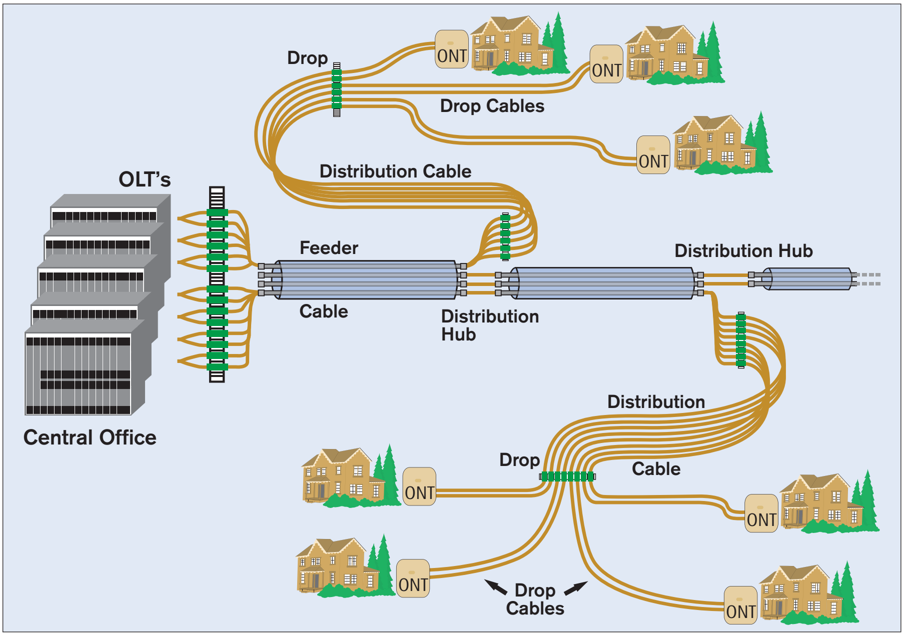


Figure 3.56 -- P2P Ethernet network topology using fiber pairs

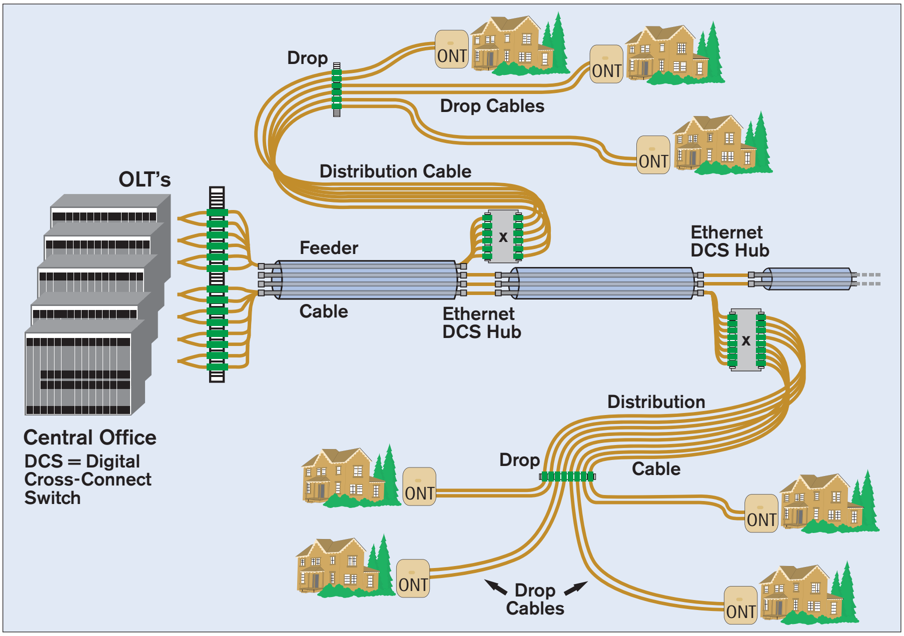


Figure 3.57 -- Active P2P Ethernet network topology using fiber pairs and switches (P2MP is also possible)

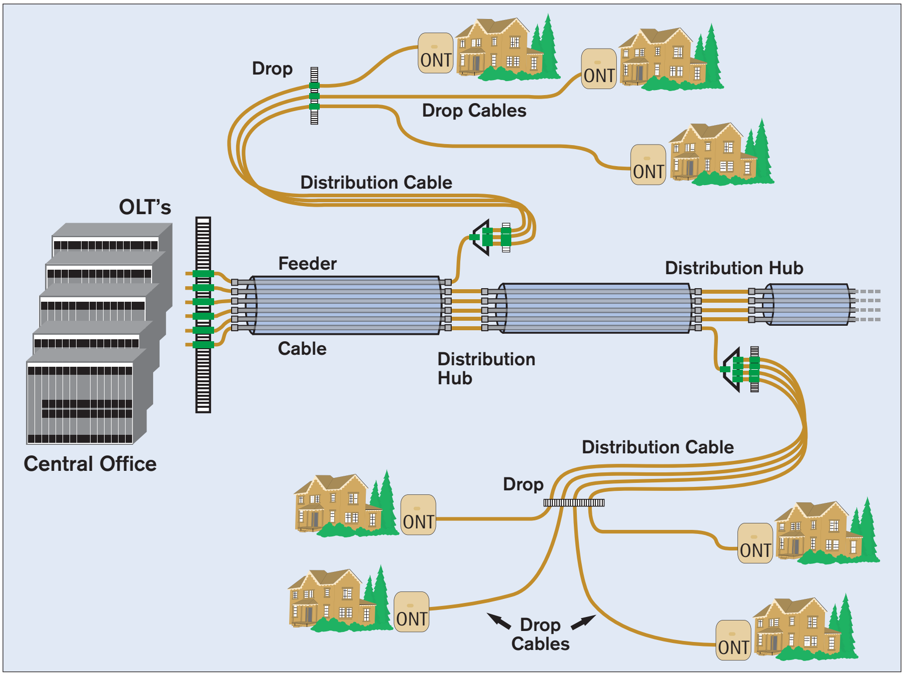


Figure 3.58 – Passive P2MP EPON topology using single fibers and splitters

Table 3.26 – Most critical differences between BPON, GPON and EPON

		BPON	GPON	EPON	
Standard		ITU-T Rec.		IEEE 802.3ah-2004	
		G.983.x	G.984.x	1000BASE-PX10	1000BASE-PX20
Max. logical reach (KM)		20	60 10		20
Max. Bit rate (Mbit/s)		1244.16	2488.32	Fixed at 1250 (nominal 1000)	
Protocol		ATM		Ethernet Multi Point Media Access Control Protocol (MPCP)	
			GEM[1]		
Tx laser	Down	DFB			
	UP	FP			DFB
Rx detector	Down	PIN			APD
	Up				
Max. Split ratio				1 x 16	
		1 x 32		1 x 32 (with FEC or DFB/APD)	
			1 x 64		

[1]ATM/TDM/Ethernet over GEM

The 10 km reach of the 1000BASE-PX10 architecture was first developed according to the following rationales:

- The 10 km link covers the majority of Japanese and European loops
- The 10 km link also covers the majority of enterprise (business) loops in North America.

In the former, the access market is mainly directed to high-rise apartment buildings.

In the latter, the enterprise network is already using Ethernet in their LANs, making the interface with the access network simpler and more cost-effective than BPON and GPON.

The main characteristics of EPON are as follows:

- P2MP topology for only full-duplex links/full-duplex (symmetric) media access control (MAC)
- Passive optical splitter (1 x 16 splitting ratio; 1 x 32 is possible but with the use of forward error correction or FEC)
- MAC control sublayer
- Reconciliation sublayer
- Optical fiber cable physical-medium-dependent (PMD) sublayer
- One singlemode optical fiber
- 1490 nm downstream wavelength for voice and data transmission
- 1310 nm upstream wavelength for voice and data transmission
- Analog video service is transported on 1550 nm but is not included in EPON architecture. It is transmitted over the same fiber (it could be fully incorporated when digital and especially IP video become available).
- Physical-layer signaling:
- 1000BASE-PX10 (1000 Mb/s up to 10 km)
- 1000BASE-PX20 (1000 Mb/s up to 20 km)
- Optional FEC (to increase the split ratio or maximum reach)
- Operations, administration and maintenance (OAM) for PON operation management and troubleshooting

Table 3.27, Table 3.28 and Table 3.29 show the EPON PMD specifications:

Table 3.27 – EPON physical-medium-dependent specifications

Standard			IEEE 802.3ah-2004	
			1000BASE-PX10	1000BASE-PX20
Protocol			Ethernet-based MPCP (+ FEC optional)	
Optical Fiber (single-mode)	Type (compatible)	ITU-T	Rec. G.652.A or G.652.C	
		IEC	IEC 60793-2-50 B1.1 or B1.3	
	Number		1	
Maximum Physical Distance (km)			10	20
Split Ratio			1 x 16 (1 x 32 with FEC or DFB-APD)	
Data Rate (Mbit/s)			1250 (1000 nominal) symmetric	

FEC: Forward Error Correction
PIN: Positive-in-Negative; APD: Avalanche Photo-Diode
MPCP: Multi-Point (Media Access) Control Protocol
G.652.A/60793-2-50 B1.1 = water-peak fiber; G.652.C/60793-2-50 B1.3 = low-water peak

The multipoint (media access) control protocol (MPCP) will be studied in detail below. The singlemode fiber used in EPONs is the same type as the one used in BPONs and GPONs. It is a dispersion-unshifted fiber that has zero chromatic dispersion in the 1310 nm region, as specified in ITU-T Recommendation G.652 and IEC 60793-2-50 (these standards are equivalent). Early on, this fiber typically had high-water-peak absorption in the 1383 nm region, much higher (sometimes even more than 2 dB/km) than at any other wavelength. Since the late 1990s, however, the manufacturing process has been tremendously improved based on successful research and understanding of the chemical processes involving the growth of that water peak. Numerous papers have since been published on the subject. But the most important contribution has been the international standardization of the improved G.652 fiber. Today, Recommendation G.652 has been divided into four categories: the first set of two is based on PMD specifications, and the other set of two is based on the presence or absence of the water peak:

- G.652.A fiber has a water peak and a PMD of less than 0.5 ps/√km
- G.652.B fiber also has a water peak but with an improved PMD down to 0.20 ps/km
- G.652.C fiber has low water peak, with the same PMD specification as G.652.A
- G.652.D fiber also has low water peak but with the same PMD specification as G.652.B.

The fiber of choice for PON is G.652.A-type fiber, which has already been deployed for the overlaid market, whereas for the new Greenfield market, G.652.C-type fiber is preferred.

EPON also has a shorter maximum reach (10 km) in 1000BASE-PX10 than BPON because of its lower power budget, lower cost equipment and less rugged protocol format (ATM vs. Ethernet). 1000BASE-PX20 has a better reach (20 km, equivalent to BPON) thanks to the use of a better ONU transmitter (based on DFB lasers) and receiver (based on APD detectors) combination. Moreover, both 1000BASE-PX10 and –PX20 have a smaller split ratio than BPON. In order to improve the maximum reach or the maximum split ratio, forward error correction (FEC), typically based on Reed-Solomon coding format, can be used. All this may obviously negatively affect the EPON cost-performance advantage against BPON. This is why EPON is seen as a mid-reach/mid-split ratio solution useful for densely populated areas and overlaid network market.

Figure 3.58 shows the EPON wavelengths, bands and spectral widths of the lasers used downstream and upstream.

The wavelengths and bands are the same as for the other systems (BPON and GPON).

GPON is considered much more powerful and flexible than EPON, but EPON is simpler and more adaptable to short-reach high-bandwidth applications such as apartment buildings or enterprise networks.

A new MAC Ethernet protocol (other than the WLAN-based IEEE 802.11

protocol for instance) was developed for EPON special requirements and evolution of IEEE 802.3. Consequently, a new multipoint MAC control sublayer,along with the related protocol–called multipoint MAC control (MPMC) protocol (MPCP)– were created. The OLT uses a MAC protocol the MPCP instance for each ONT, whose layer determines which logical ONT is active at any single point in time. This ensures that the EPON P2MP MAC fits into the Ethernet specifications. Figure 3.54 shows the EPON P2MP architecture.

Table 3.28 -- EPON physical-medium-dependent transmitter and receiver specifications

Standard			IEEE 802.3ah-2004			
10			00BASE-PX10		1000BASE-PX20	
			OLT	ONU	OLT	ONU
Transmitter	λ (nm)		1490	1310	1490	1310
	Band (nm)		1480-1500	1260-1360	1480-1500	1260-1630
	Laser type		DFB	FP	DFB	FP
	Averaged launched power (dBm)	Maximum	+2	+4	+7	+4
		Minimum	-3	-1	+2	-1
	Reflectance (dB)		-10	-6	-10	
	Penalty (dB)		1.3	2.8	2.3	1.8
Receiver	λ (nm)		1310	1490	1310	1490
	Band (nm)		1260-1360	1480-1500	1260-1360	1480-1500
	Detector type		PIN		APD	PIN
	Averaged received power (dBm)		-1	-2	-6	-3
	Damage Threshold	Maximum	+4	+2	+4	+7
	Sensitivity		-24		-27	-24
	Reflectance (dB)		-12			

PIN: Positive-in-Negative; APD: Avalanche Photo-Diode

Table 3.29 -- EPON physical-medium-dependent link specifications

Standard		IEEE 802.3ah-2004			
		1000BASE-PX10		1000BASE-PX20	
Traffic Direction		Down	Up	Down	Up
Optical Return loss (dB)	Maximum	15			
	Minimum	20			
Power Budget (dB)	Without FEC	21	23	26	
	With FEC[1]	23.5	25.5	28.5	
Penalty Allocation (dB)		1.5	3	2.5	2
Chromatic Dispersion (CD)	ε(Epsilon model)	0.115		0.1	
	Maximum Penalty (dB)	2		1.5	

[1]Under dispersion limit
ε (epsilon model) = *CD*(ps/nm) x *L* x *BR*(Gbit/s) x $\Delta\tau_{RMS}$(nm) x 10^{-3}
FEC: Forward Error Correction

MACs are uniquely identified by their Logical Link ID (LLID), which is dynamically assigned by the registration processing. A MAC client ONT transmits and receives IEEE 802.3 frames through the MPMC sublayer. MPMC uses the client interface control multiplexer to decide when a frame should be transmitted over its timeslot. It can generate higher priority control to transmit MPCP frames before the MAC client frames. The frame transmit mode accepts data from MAC client, constructs the frame, and presents a bit-serial data stream to the physical layer (PHY) for transmission. The frame receive mode receives a bit-serial data stream to the PHY for transmission, presents it to the MAC client sublayer broadcast or directly addressed frames and defers transmission if PHY is busy. For the frame structure itself, the frame receive mode appends the preamble, start-of-frame delimiter, destination address (DA), source address (SA), length/type field and frame check sequence (FCS) to all frames. It also removes preamble, start-of-rame delimiter, DA, SA, length/type field and FCS from all received frames. The structure of the IEEE 802.3 frame is shown in Figure 3.59.

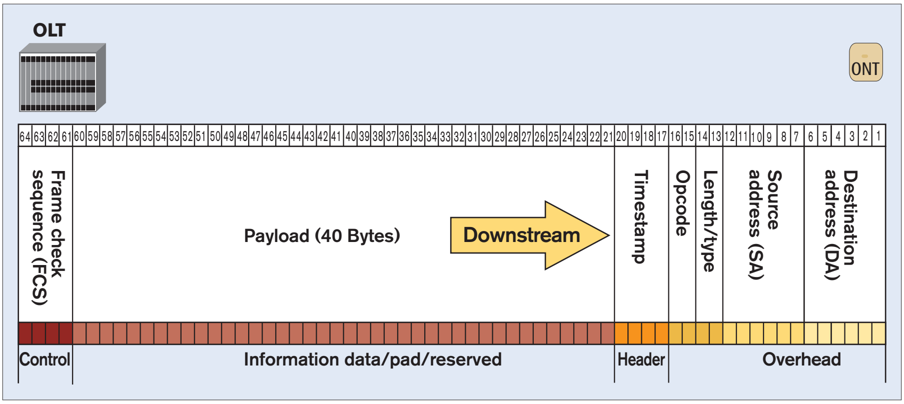


Figure 3.59 – Basic IEEE 802.3 frame structure

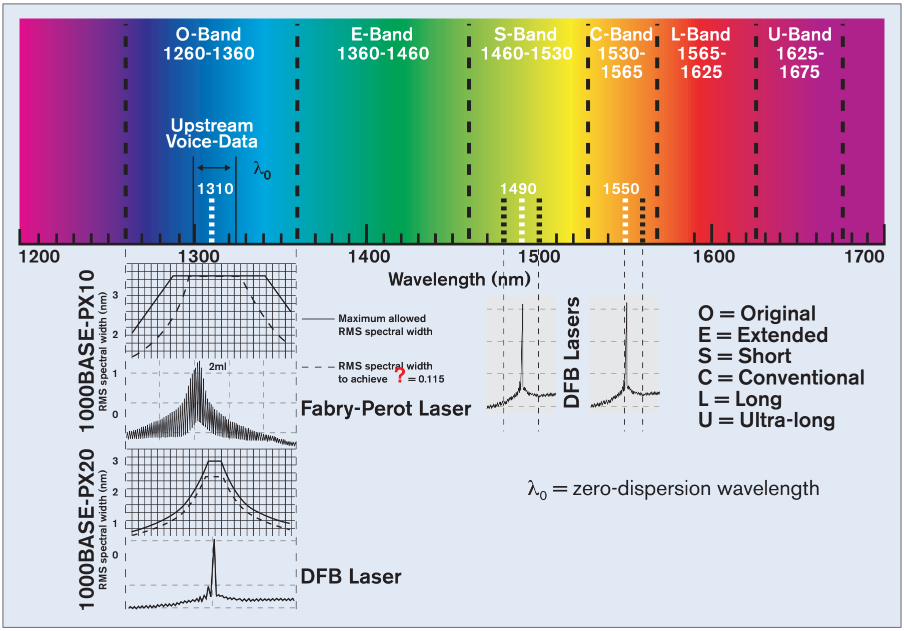
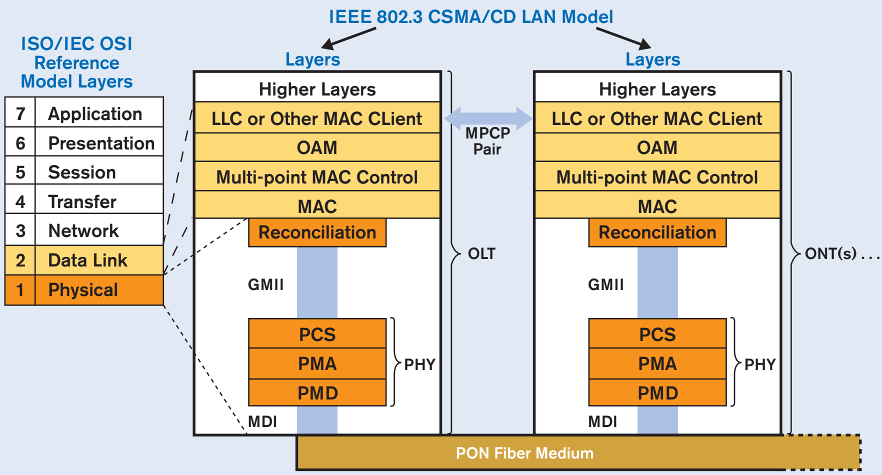


Figure 3.60 -- EPON wavelengths and bands



CSMA/CD: Carrier-sense multiple access with collision detection
GMII: Gigabit media-independent interface
LLC: Logic link control
MAC: Media access control
MDI: Medium-dependent interface
OAM: Operations, administration and maintenance
OSI: Open-systems interconnection
PCS: Physical coding sublayer
PHY: Physical-layer device
PMA: Physical medium attachment
PMD: Physical-medium-dependent

Figure 3.61 – EPON P2MP architecture

The MPCP uses a number of processes to manage transport and communication of the services. The OLT discovers and registers an ONT through the discovery processing using a GATE message. The ONT generates REPORT messages to the OLT, including ONT bandwidth requirements. The process is called REPORT processing. Fine control of the network bandwidth distribution is achieved using feedback mechanisms from these messages. The OLT generates GATE messages to the ONT, and multiplexing of multiple ONT transmitters is achieved. The process is called GATE processing. Multiple-MAC operation only allows a single MAC to transmit upstream at any given OLT-granted timeslot across the network using a time-division multiple access (TDMA) method. This basic process is founded on the same discovery and timeslot allocation logic as BPON and GPON. The GATE and REPORT processes are illustrated in Figure 3.2.

Essentially, the OLT provides GATE messages downstream, while ONTs provide REPORT messages upstream.

The discovery processing is driven by the OLT, where one or more newly connected or off-line ONTs are provided PON access. The discovery time window (DTW), during which off-line ONTs make themselves known to the OLT is periodically made available. The OLT broadcasts a discovery gate message (DGM) to the ONT, which includes DTW starting time and length. Upon receiving the DGM, the ONT(s) wait(s) for the DTW to begin and then transmit(s) a

REGISTER_REQ message to the OLT. Multiple valid REGISTER_REQ ONT REPORT messages can be received by the OLT during a single DTW. The REGISTER_REQ message contains the ONT's MAC address and a number of maximum pending grants. Upon receiving a valid REGISTER_REQ message, the OLT registers the ONT, allocates and assigns a new ONT port identity (LLID), linking corresponding MAC to the LLID.

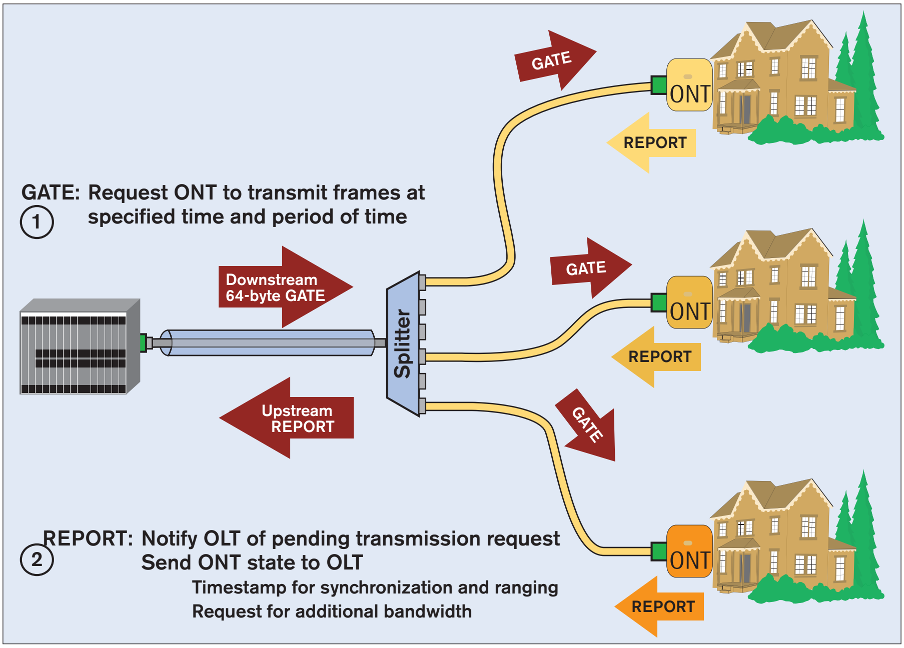


Figure 3.62 – EPON GATE and REPORT processes

The OLT has a master clock, while the ONTs each have their own local clock. Both clocks have a 32-bit counter, incrementing every 16 ns. The counter provides a local timestamp. At regular intervals, the OLT transmits an MPCP GATE message to the ONTs. The OLT counter value is mapped into the timestamp field of the message. The transmission time from the MAC control to the MAC of the first frame byte is taken as the reference time used for setting the timestamp value. In reception, the ONT sets its counter according to the value in the received timestamp field. The OLT uses this value to calculate or verify the OLT-ONT round-trip time (RTT), which is equal to the difference between the timer value and the timestamp field value. The RTT is also notified to the client via the MA_CONTROL indication primitive, and it is used by client ONT for ranging processing.

At regular intervals, the OLT transmits an MPCP GATE message to the ONTs. The OLT message is then time-marked. The OLT uses this technique to range the ONTs by calculating their round-trip time (from the RTT) and ensure proper controlled transmission timeslot (grant time) for each ONT. This process is described in Figure 3.63

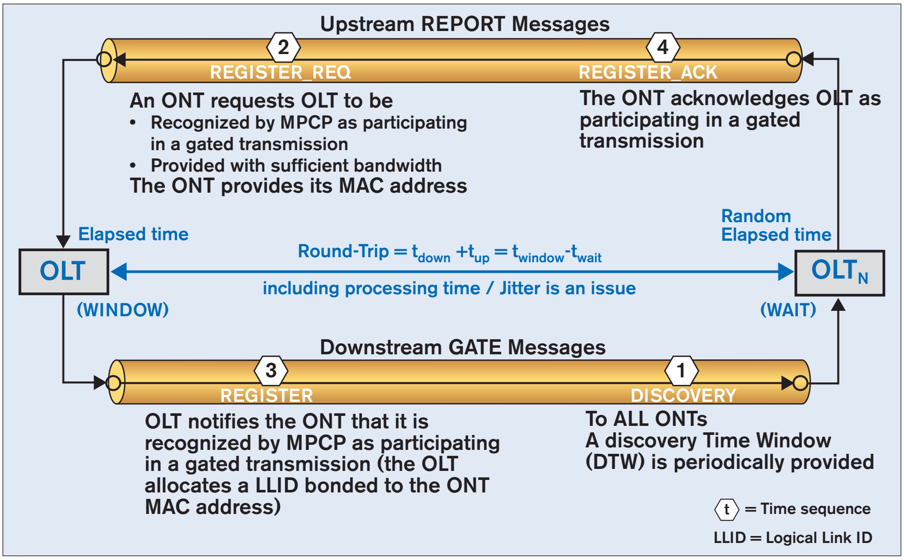
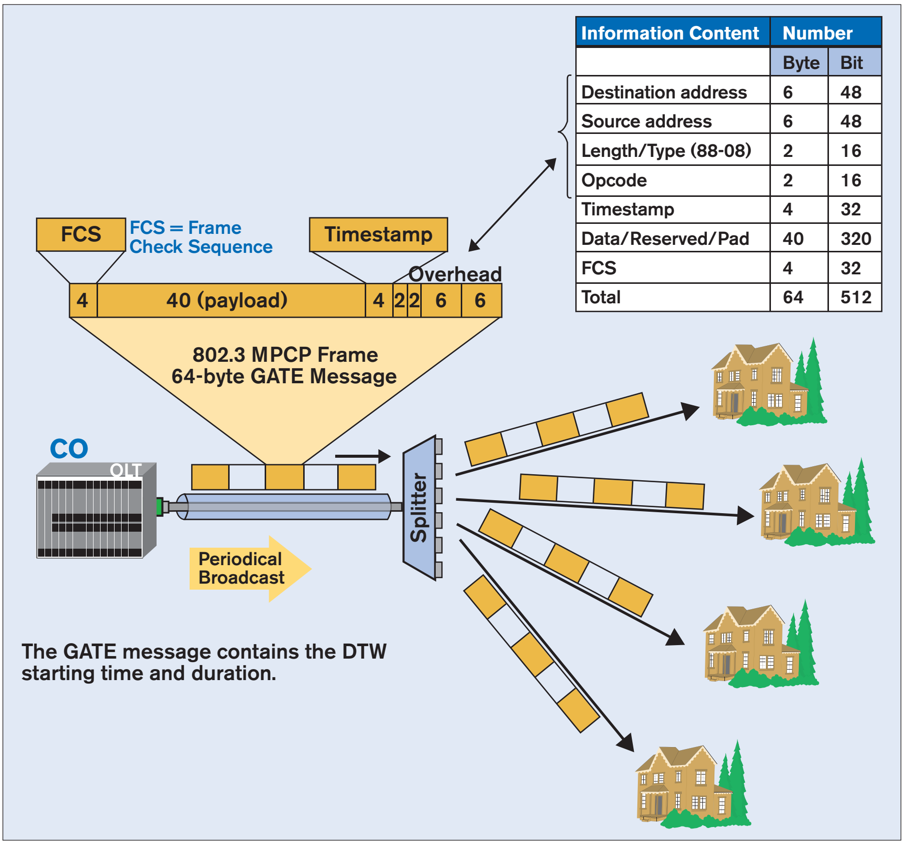


Figure 3.63 – Communication processing between the OLT and an ONT



Information Content	Number	
	Byte	Bit
Destination address	6	48
Source address	6	48
Length/Type (88-08)	2	16
Opcode	2	16
Timestamp	4	32
Data/Reserved/Pad	40	320
FCS	4	32
Total	64	512

Figure 3.64 -- Downstream discovery process with GATE message

The OLT controls ONT transmissions by assigning grants. The ONT DTW is indicated in the GATE message where start time and duration are specified. The ONT begins transmission when its Local Time counter matches the start time value indicated in the GATE message. The ONT also concludes transmission with sufficient margin to ensure that the laser is turned off before the grant duration has elapsed. Multiple grants may be issued by the OLT to each ONT. The GATE message frame is illustrated in Figure 3.63. The discovery process is illustrated in Figure 3.65.

The MPCP GATE discovery message payload is illustrated in Figure 3.65.

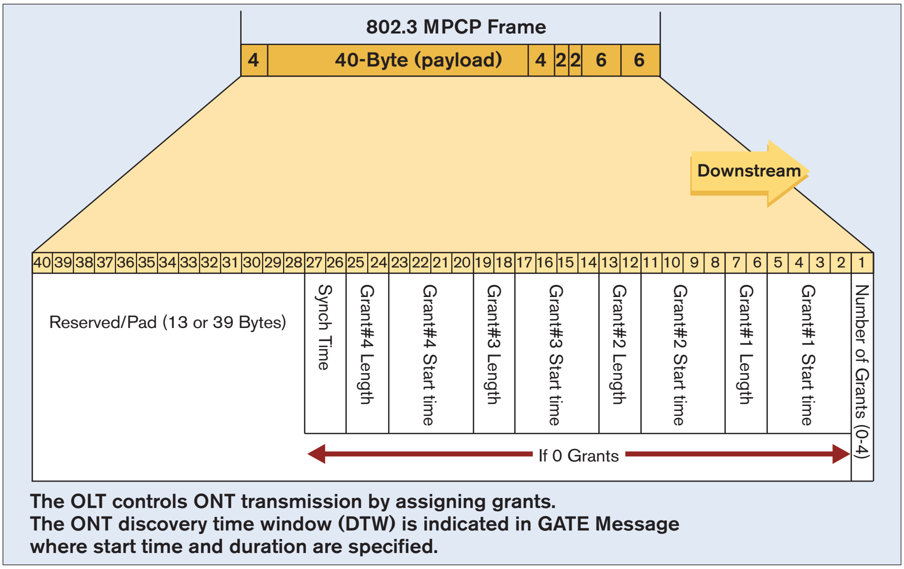


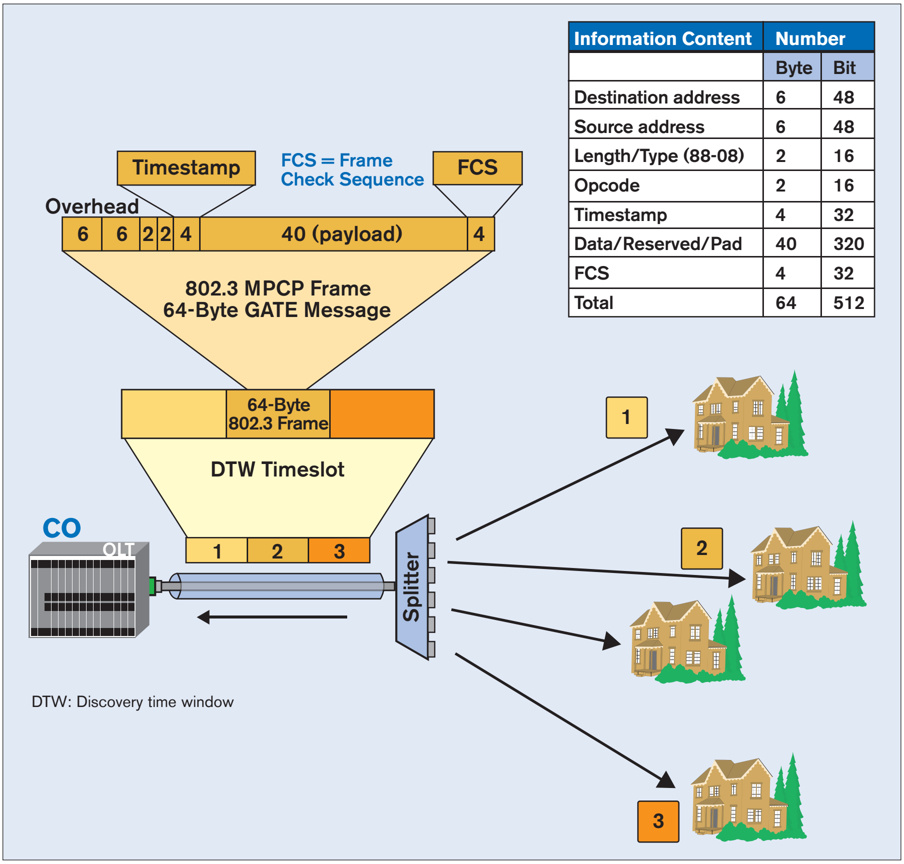
Figure 3.65 -- MPCP GATE granting message payload

Up to four transmission windows can be granted by a single GATE MPCP message.

Upon receiving the discovery GATE message, the off-line ONT(s) request(s) permission from the OLT to participate in the transmission communication processing. It waits for the DTW to begin and then transmits a REGISTER_REQ REPORT message containing a request for registering. The report processing deals with queue report generation and termination in the PON. The report processing is generated periodically by the higher layers and passed on to the MAC control sublayer by the MAC control clients. It is also used to signal ONT bandwidth needs, as well as to arm the OLT watchdog timer. Multiple valid REGISTER_REQ REPORT messages may be sent to the OLT during the DTW. Figure 3.66 illustrates the upstream REGISTER_REQ reporting process.

Figure 3.67 shows the MPCP REGISTER_REQ REPORT message payload.

Periodically, the ONT can send a queuing REPORT message to the OLT. In this case, only the payload is different in the message structure. Figure 3.67 shows the MPCP queue REPORT payload.



Information Content	Number	
	Byte	Bit
Destination address	6	48
Source address	6	48
Length/Type (88-08)	2	16
Opcode	2	16
Timestamp	4	32
Data/Reserved/Pad	40	320
FCS	4	32
Total	64	512

Figure 3.66 -- Upstream MPCP REGISTER_REQ reporting process

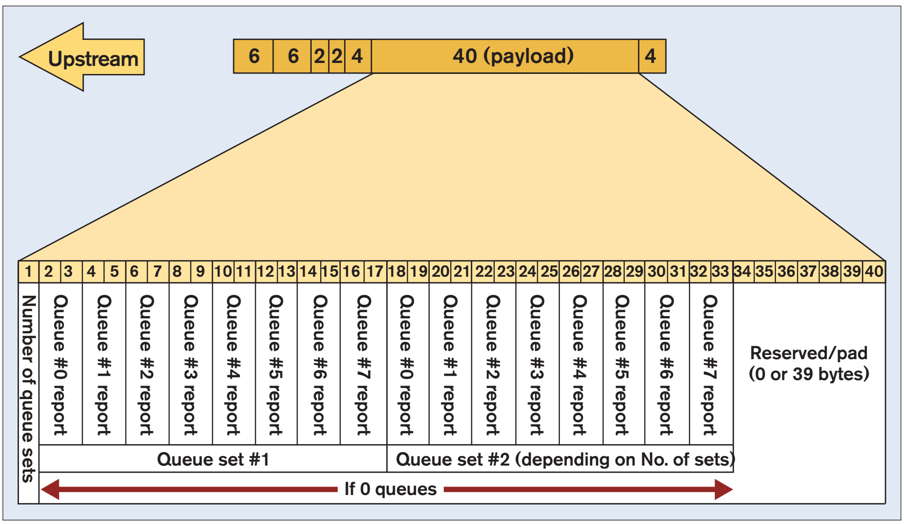


Figure 3.67 -- MPCP REGISTER_REQ REPORT message payload

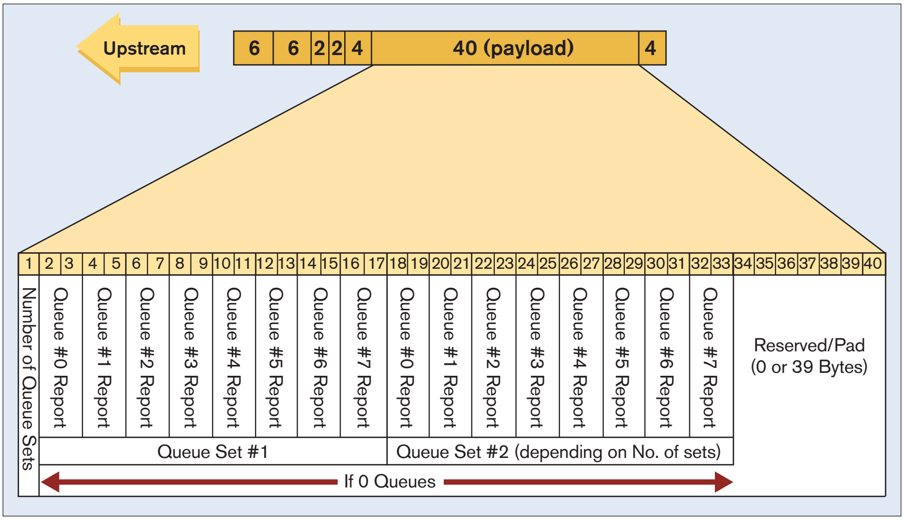


Figure 3.68 -- MPCP queue REPORT message payload

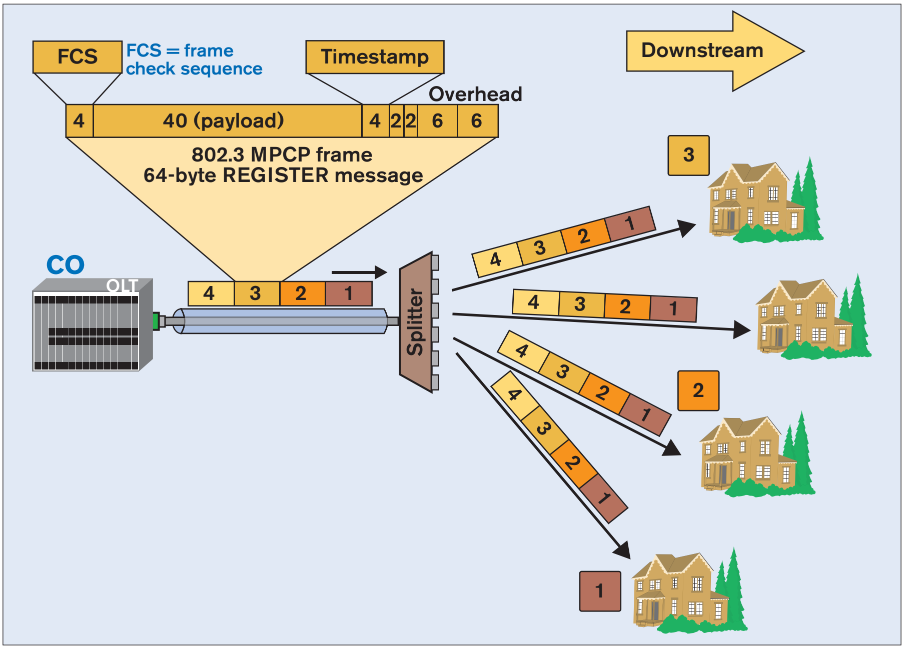


Figure 3.69 -- Downstream GATE register message process

Each ONT can support up to 256 queue sets, each of which has eight queues. The ONT reports its bandwidth needs for each queue set and queue by means of the REPORT message. The OLT then uses the information contained in the ONT REPORT messages on the queue statuses for setting the upstream transmission schedule. The number of queues per set is chosen in order to match the priorities set in IEEE 802.1q. This concept is intended for use where

EPON is used to connect multiple subscribers in a multidwelling unit.

When the conditions (ONT discovery, granting, acknowledgment reporting) for successful ONT transmission are met, the OLT transmits a GATE register message (as shown in Figure 3.69 and Figure 3.70) to the newly discovered ONT. The register message contains the ONT's identification and the OLT's required synchronization time. ONT MACs are uniquely identified by their LLID, which is dynamically assigned by the registration process, as shown in Figure 3.71.

The MPMC does not support authentication; but the GATE REGISTER message provides mechanisms for reporting authentication failures.

The OLT echoes the maximum number of pending grants, schedules the ONT for PON access and transmits a standard GATE message allowing the ONT to transmit a REGISTER_ACK REPORT message. Upon receiving the ONT's REGISTER_ACK REPORT message, the OLT may then require the ONT(s) to go through the discovery sequence again and reregister.

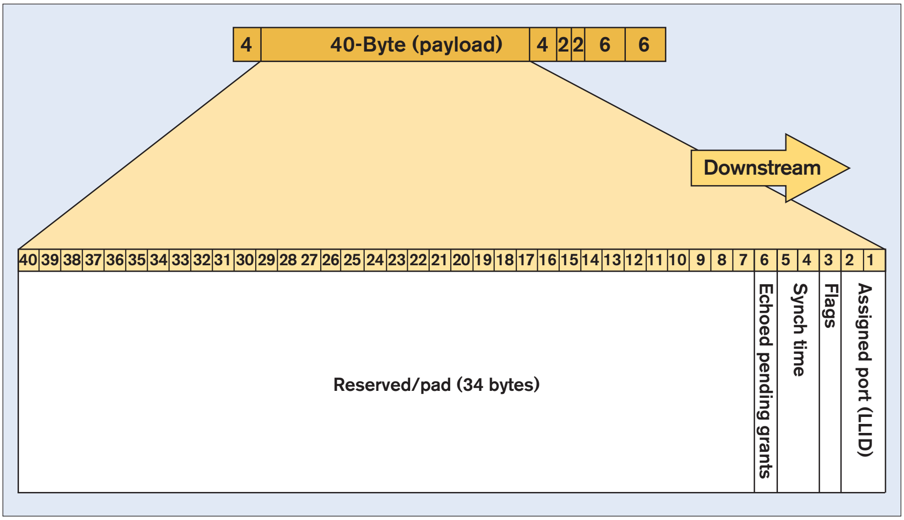
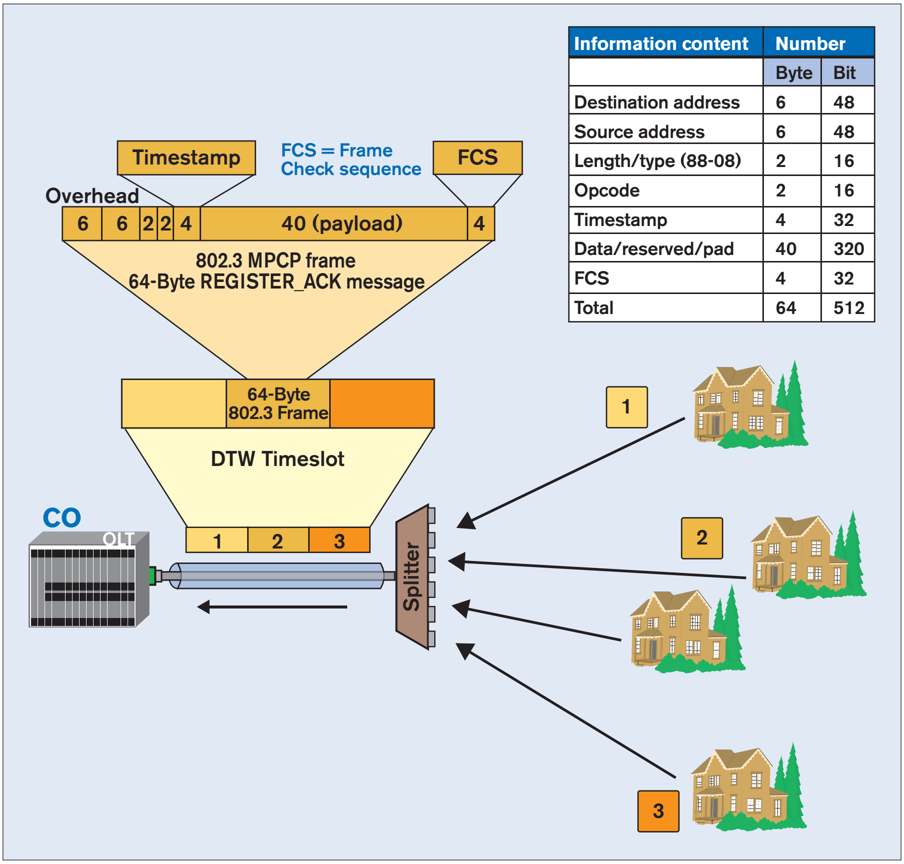


Figure 3.70 -- MPCP GATE register message payload

Upon receiving the GATE REGISTER message, the ONT(s) wait(s) for the DTW to begin and then transmit(s) a REGISTER_ACK REPORT message to the OLT. Multiple valid upstream REGISTER_ACK REPORT messages can be sent to the OLT during a DTW. The details of the upstream REGISTER_ACK REPORT message illustrated in Figure 3.71 and its payload is shown in Figure 3.72.

At that time, the ONT discovery process is complete. The ONT is registered and normal message data traffic can begin. However, the ONT may need to inform the OLT for deregistering and then register again by going through the same discovery processing.



Information content	Number	
	Byte	Bit
Destination address	6	48
Source address	6	48
Length/type (88-08)	2	16
Opcode	2	16
Timestamp	4	32
Data/reserved/pad	40	320
FCS	4	32
Total	64	512

Figure 3.71 -- Upstream REGISTER_ACK Reporting Process

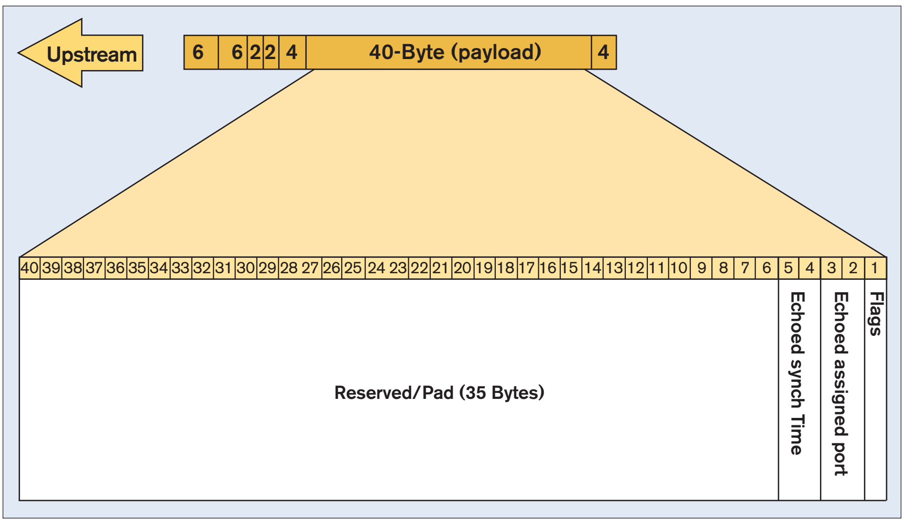


Figure 3.72 -- MPCP REGISTER_ACK REPORT message payload

The MPCP ranging and timing processing can be summarized as follows:

- Both OLT and ONT have a 32-bit counter incrementing every 16 ns
- The counter provides a local timestamp
- In transmission, the OLT/ONT maps its counter value into the timestamp field
- The transmission time from the MAC control to the MAC of the first frame byte is taken as the reference time used for setting the timestamp value
- In reception,
  - The ONT sets its counter according to the value in the received timestamp field.
  - The OLT uses the received timestamp value to calculate or verify an OLT-ONT round-trip time (RTT):
    - Equal to the difference between the timer value and the timestamp field value
    - Notice to the client via the MA_CONTROL indication primitive
    - Used by client ONT for ranging processing.

The data logical operations are summarized as follows:

Frame Transmission:

- Accepts data from MAC client
- Constructs a frame
- Presents a bit-serial data stream to the physical layer (PHY) for transmission

Frame Reception:

- Receives a bit-serial data stream to the PHY for transmission
- Presents to the MAC client sublayer broadcast or directly addressed frames
- Defers transmission if PHY is busy
- Appends preamble, start-of-frame delimiter, destination address, source address, length/type field and frame check sequence (FCS) to all frames
- Removes preamble, start-of-frame delimiter, destination address, source address, length/type field and frame check sequence (FCS) from all received frames

When the OLT MPCP (GATE message) is received by an ONT, the ONT's local clock is adjusted to the received value. When an ONT transmits, a time marker (timestamp) is inserted, indicating the ONT MPMC transmit time measured by the ONT local clock. When the OLT receives the ONT information, it can calculate the RTT between the OLT and the transmitting ONT.

The MPCP does not support authentication; but the REGISTER message provides mechanisms for reporting authentication failures.

3.5.4.4 Downstream data broadcast mode from OLT

The OLT downstream transmission is constantly broadcasting data information to ONTs, similar to the BPON downstream data transmission process. Figure 3.73 illustrates the process.

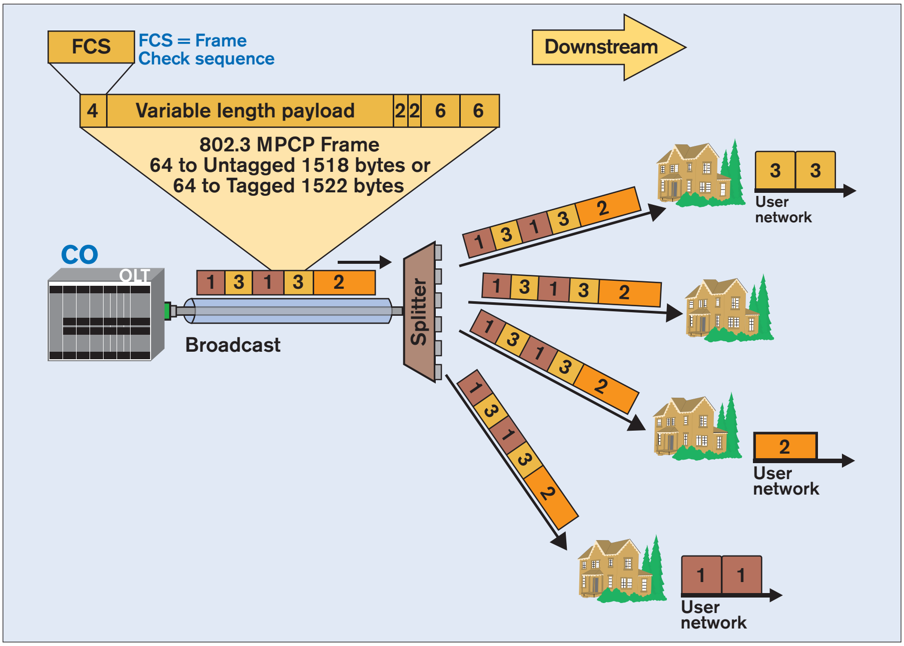


Figure 3.73 – EPON OLT downstream data broadcast transmission process

The difference between the MPCP 802.3 frame and the 802.3 data frame is that the MPCP 802.3 frame has a fixed length of 64 bytes, while the data frame has a variable length (from 64 bytes to 1518 untagged bytes or to 1522 tagged bytes) depending on the payload length. The data frame still uses the same 16-byte overhead and 4-byte frame check sequence (FCS). However, it does not need the 4-byte timestamp anymore, as it does not use the RTT counter.

3.5.4.5 Upstream transmission from ONT

The upstream ONT transmission is also controlled by the multipoint control protocol (MPCP). Time slots are defined based on the longest message sent by any ONT. A time slot may contain 802.3 frames from each transmitting ONT. Figure 3.74 shows how the various ONTs transmit to the OLT in accordance with their bandwidth requirements, the time slot is allocated based on the maximum bandwidth required and the 802.3 frame.

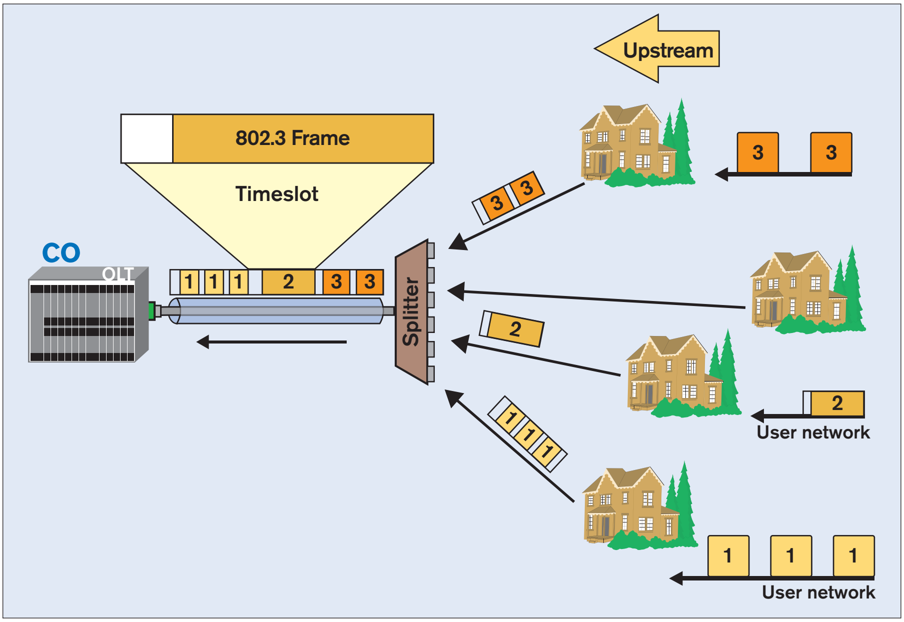


Figure 3.74 – EPON ONT upstream transmission processes

3.5.4.6 Forward error correction (FEC) in EPON

Forward error correction (FEC) has been used for quite a while since the development and deployment of optical transport networks. Two techniques have been proposed and successfully applied: Bose-Chaudhuri-Hocquenghem (BCH) and Reed-Solomon (RS). Table 3.30 gives an overview of each technique and their characteristics. FEC is specified in ITU-T Recommendation G.975 (2000), entitled *Optical fiber submarine cable systems - Forward error correction for submarine systems.*

Table 3.30 – Coding techniques for forward error correction (FEC)

	1000BASE-PX10	1000BASE-PX20
Code name	BCH[1]	RS[2](255,239)
Nob. of bits per symbols	1	8
Nob. of data symbols	4320	239
Nob. of overhead redundant parity symbols	39	16
Total nob. of symbol per codeword	4359	255
Original OTN system application	1-channel SDH	Submarine
Bit rate increase	No	Yes
BER upper limit	2.9×10^{-6}	1.9×10^{-4}
Coding gain[3] (dB)	3.8 dB	5.9 dB
Max. nob. of corrected error symbols per codeword	3	8
Max. nob. of corrected continous symbols	24 per STM-64 or STM-256 row	1024

[1] Bose-Chaudhuri-Hocquenghem
[2] Reed-Solomon
[3] @ 10-12 BER yield after FEC
OTN: Optical transport network
SDH: Synchronous digital hierarchy
BER: Bit error rate (ratio in ITU-T)
STM: Synchronous transfer mode

The FEC code used in EPON[6] is a linear cyclic block code. The code used is the Reed-Solomon (RS) code (255, 239, 8) over Galois Field (2^8), a non-binary code operating on eight-bit symbols.
The main characteristics of the EPON FEC is described in Table 3.32.

Table 3.31 – EPON forward error correction (FEC) characteristics

	EPON FEC Characteristics
Code name	**RS(255,239)**
Coding gain (dB)	
For dispersion unlimited links	**2.5**
Other cases (4-5 km improvement)	**2.0**
Applications	**Reduce penalty due to FP laser MPN**
	Increase 1000BASE-PX10 reach to 20 km
	Increase 1000BASE-PX1split ratio to 1 x 32

FEC: Forward error correction
RS: Reed-Solomon
BER: Bit error rate (ratio in ITU-T)
MPN: Mode partition noise

The FEC machine is made of:

- FEC Encoder
- FEC Decoder
- FEC Synchronization

All these elements have a 10-bit interface (TBI) to both sides and can be omitted for applications not requiring FEC. The FEC machine is implemented in P2MP physical layer at TC Layer.

The Ethernet packets are received from the physical coding sublayer (PCS). The data is then partitioned into 239 symbol frames called blocks provided to FEC. Each block is encoded by the RS encoder. The encoder adds 16 parity redundant symbols added at the end of each block. The 239 data symbols added to the 16 parity symbols give the 255 symbols RS codeword. The Ethernet frame is made of a number of blocks and special start and stop markers immune to noise (at least five bytes long). The information symbols are not disturbed in any way in the encoder and the parity symbols are added separately to each block. The machine is very efficient; as an example, an input BER of 10^{-4} can be improved up to 10^{-12} to 10^{-15}. However, the technique is not perfect and has some limitations at very high BER. For instance, at a BER of 10^{-3}, the technique will generate decoding errors.

Forward error correction (FEC) is used to increase:

- Optical link budget
- Fiber distance

Additional data is provided

- To the Ethernet frame
- From a set of non-binary arithmetic functions (known as Galois arithmetic) performed on the frame data
- known as the FEC parity bytes
- To correct errors at the receiving end of the link when the data is transferred through the link

The FEC code used in EPON is:

- A linear cyclic block code
  - Reed-Solomon code (255, 239, 8) over GF(28) Galois Field – a non-binary code operating on eight-bit symbols
- Encoding 239 information symbols
- Adding 16 parity symbols
- Systematic form of the RS code
  - The information symbols are not disturbed in any way in the encoder and the parity symbols are added separately to each block.
- Used by the transport layer in communication systems
- Based on transmitting data in encoded format
- Encoding introduces redundancy, allowing the decoder to detect and correct transmission errors
  - Block-based code
  - Adds extra ‘redundant’ bits at the end of constant-size data block
- E.g., $BER_{input} = 10^{-4}$ results in $BER_{output} = 10^{-15}$
- Most common code = RS(255,239)
- Codeword
  - 255 bytes long
  - 239 data bytes
  - Followed by 16 OH redundant bytes
- Original data preserved
- Not efficient for very high BER (e.g. will generate decoding error for 10^{-3} BER)

In EPON/GPON (Recommendations G.984.2 and G.984.2), FEC has the following characteristics:

- P2MP physical layer
- Implemented in TC Layer
- Transmits characters inserted at packet end between frames
- 2.5 dB gain improvement for non-dispersion limited links
- 2.0 dB in other cases (4-5 km improvement)
- Applications with Fabry-Perot laser
- FEC reducing penalty due to mode partition noise (MPN)
- $10 < \text{link length (km)} > 20$
- 1 x 32 split at 10 km

3.5.4.7 Operation, administration and maintenance (OAM)

The OAM layer adds capabilities for remote failure detection, remote loopback, link monitoring and polling of management information base (MIB) variables. However, it does not include functions for protection switching, service provisioning, link adaptation, and security related functionalities.

3.5.4.8 Summary of Ethernet architectures

Table 3.32 on the next page provides a summary of all the available Ethernet fiber-optic architectures, including EPON.

[6] *FEC can also be used in GPON*

Table 3.32 – Summary of available Ethernet fiber-optic architectures

Ethernet Network	Standard	Bit Rate Mbit/s	Architecture: Transport Medium	Medium Type	Link Type	Wavelength nm	Max. Reach km	Application
100Mbit	100BASE-LX10	100	SMF pair	G.652	P2P	1310	10	
	100BASE-BX10		SMF single bi-dir		P2P (w switch)	1310 Up/ 1550 Down		
1GbE	1000BASE-SX	1000	62.5µ MMF pair	ISO1 1801 OM1	P2P	850	<0.3	LAN 8B/10B
			50µ MMF pair	ISO1 1801 OM2			0.55	
				ISO1 1801 OM3			1	
EFM	1000BASE-LX		62.5µ MMF pair	ISO1 1801 OM1		1300	0.3	
			50µ MMF pair	ISO1 1801 OM2			0.55	
				ISO1 1801 OM3			1	
			SMF pair	ISO1 1801 OM1		1310	2	
	1000BASE-LX10			G.652			10	
	1000BASE-BX10		SMF single bi-dir	G.652	P2P (w switch)	1310 Upstream 1490 Downstream		
EFM PON	1000BASE-PX10	1000	SMF single bi-dir	G.652	P2MP	1310 Upstream 1490 Downstream	20	FTTH
	1000BASE-PX20							
10GbE	10GBASE-S	1000	62.5µ MMF pair	SO1 1801 OM1	P2P	850	<0.3	LAN 8B/10B
			50µ MMF pair	SO1 1801 OM2				
				SO1 1801 OM3			0.3	
	10GBASE-LX4		62.5µ MMF pair	SO1 1801 OM1		1300		
			50µ MMF pair	SO1 1801 OM2				
				SO1 1801 OM3				
			SMF pair	SO1 1801 OM1		1310	2	
	10GBASE-SR		62.5µ MMF pair	SO1 1801 OM1		850	0.033	LAN 64B/66B
	10GBASE-SW							WAN SONET
	10GBASE-SR		50µ MMF pair	SO1 1801 OM2			0.082	LAN 64B/66B
								WAN SONET
				SO1 1801 OM3			0.3	LAN 64B/66B
								WAN SONET
	10GBASE-L		SMF pair	SO1 1801 OM1 G.652		1310	10	LAN 64B/66B
	10GBASE-LR							WAN SONET
	10GBASE-ER					1550	2	LAN 64B/66B
	10GBASE-E						40	WAN SONET
	10GBASE-ER							

SMF: Single-mode fiber
MMF: Multimode fiber
bi-dir: bidirectional

Chapter 4

Description of Outside Plant Equipment

Located in the field between the CO and the customer premises, outside plant (OSP) equipment can be subject to potentially harsh conditions. OSP equipment usually refers to both optical and non-optical network components.

The **optical components** make up the optical distribution network (ODN) and include the following:

Fiber-optic cables:

- The feeder cable between the CO (WWDM coupler) and the splitter – This is usually a multifiber cable; the number of fibers correspond to the number of deployed splitters (the total number of splitters will equal the total number of subscriber ONUs).
- The distribution fibers between the splitter and the drop terminals – This may be a multifiber cable, depending on the deployment topology of the drop terminals (usually based on the topology and density of the premises deployment in an area; for instance the distribution of streets in a rural location).
- Drop cables between the drop terminals and ONUs – These are protected, single-fiber armored cables, one for each ONU; each cable is terminated with a special protected connector that withstands environmental conditions.

Splitter(s), which can be installed in one of three ways:

- Buried
- Aerial
- Inside a fiber distribution hub (as shown in Figure 4.1)

Drop terminals (such as patch panels and connectors) which can be installed in one of three ways):

- Buried
- Aerial
- Inside a pedestal

Connectors:

- SC/UPC-type connectors (ultra-polished connectors) are produced using a highly perfected polishing technique. Reflections are as low as 55 dB. UPC-type connectors are preferred if analog overlaid video is not transmitted. This connector usually has a blue protective jacket.
- SC/APC-type connectors (angled physical-contact or angled polished connectors) have an 8°-slope ferrule front end (see Figure 4.2). This results in:
    - Very low reflections (better than 60 dB) especially from the high-power video signal
    - Very low loss (better than 0.2 dB)
    - Possible sensitivity to polarization due to the angle

The typical ORL for the APC and UPC connector is as follows:

UPC: 50-55 dB ORL

APC: 67-70 dB ORL

APC-type connectors are preferred if high-power analog overlaid video is transmitted. This connector usually has a green protective jacket.

- Connector adapters of the same connector type as above are used with patch panels at the CO, at the distribution hub and at the drop terminal. They are used to interconnect two connectors from each side of the patch panel.

Figure 4.3 shows examples of small form factor (SFF) connectors and adapters using the same connector types described above and commonly used in PONs.

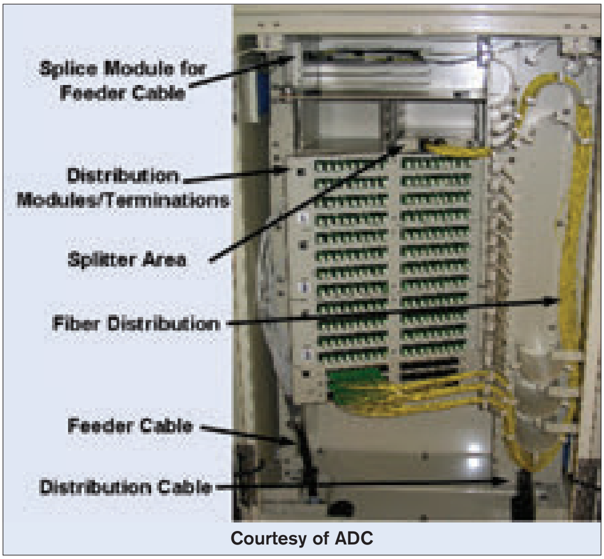


Figure 4.1 -- Typical fiber distribution hub (FDH)

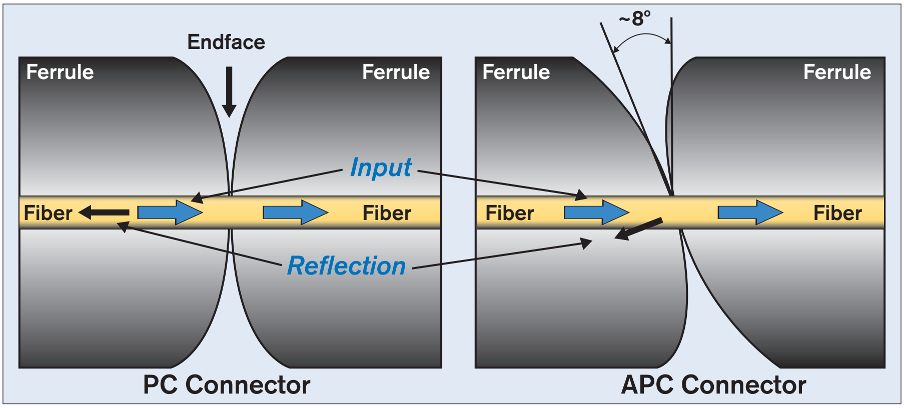
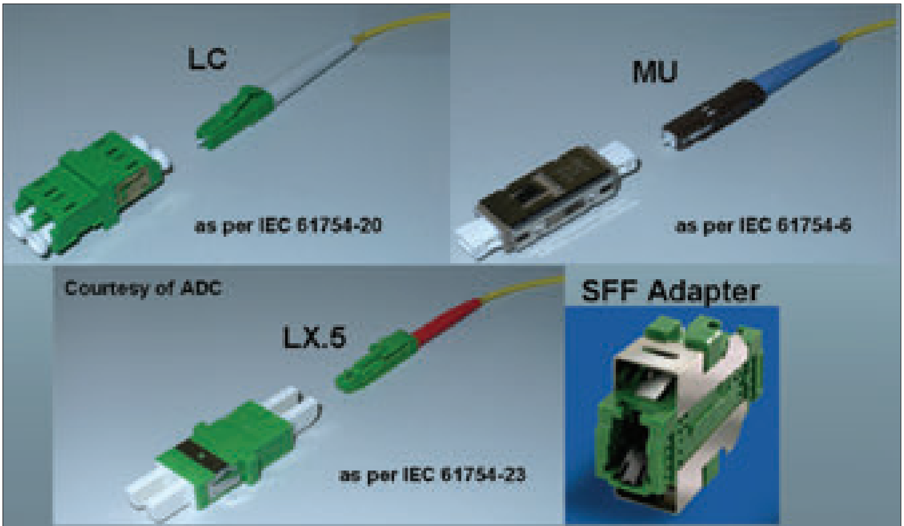


Figure 4.2 – Comparison between PC and APC connectors



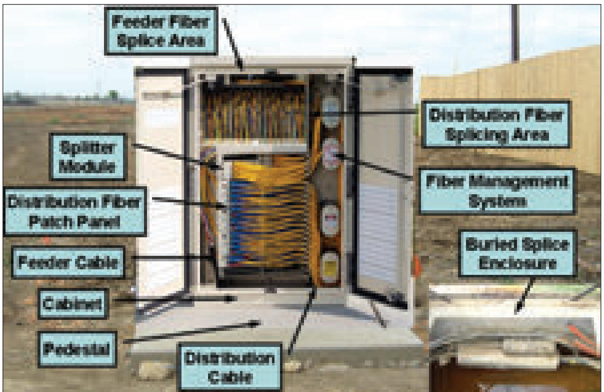
Courtesy of ADC

Figure 4.3 -- Small form factor (SFF) connectors

The **non-optical components** include pedestals, splice enclosures, vaults, patch panels, and miscellaneous hardware.

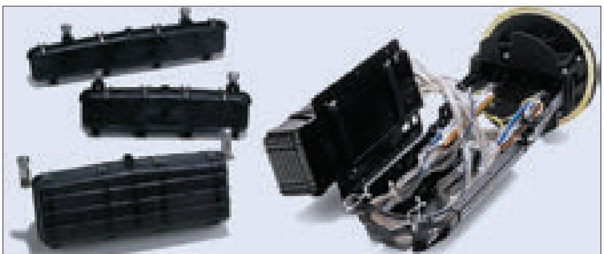
The fiber distribution hub (FDH) (as shown in Figure 4.4) includes:

- Pedestal (if installed on the ground)
- Splice enclosure (i.e., the cabinet itself). Depending on the size of the feeder cable, the splice enclosure may be located outside the FDH cabinet in the immediate vicinity; the enclosure can be aerial or buried as shown in Figure 4.5.
- Splice module for feeder cable
- Snap-in splitter module
- Distribution modules



Courtesy of ADC

Figure 4.4 – Example of an FDH with buried cable splice enclosure



Courtesy of ADC

Figure 4.5 – Examples of OSP splice closure

- Parking lot (extra space)
- Distribution cable output
- Feeder cable input
- Fiber management system and patch panel(s)
- Ducts
- Cabinets
- Pedestals
- Patch panel(s)
- Fiber management elements.

4.1 OSP Installation

Installation of OSP equipment in an FTTH PON can be carried out in many ways and each installation may be different, depending, for example, on the PON topology, the distance from the CO, residential density and distribution, etc. Fiber-optic cables can be installed using the most appropriate aerial (see Figure 4.6) or underground (see Figure 4.7) installation techniques. The placement of splitters and other passive components, as well as the types of pedestals or cabinets used will depend on geographical factors and the topology.

Figure 4.6 – Example of aerial cable installation

(a) (b)

Figure 4.7 – Example of buried cable installation

4.1.1 Fiber Cable

Fiber-optic cable installation is one of the most costly elements in PON deployment, as it is for other fiber-optic networks. Several methods are available. The choice of method depends on various factors such as cost, right-of-ways, local codes, aesthetics, etc., and on whether the installation is being performed in a new development (Greenfield installation) or in an existing development over existing routes (overlay/overbuild). Three basic cable-installation methods are available:

- Direct burial method:
  - Installing the cable underground in direct contact with the soil
  - Done by trenching, plowing or boring (as shown in Figure 4.7)
- Duct installation:
  - Installing the cable inside an underground duct network
  - More expensive than direct burial installation
  - Lower maintenance cost than direct burial (much easier to add or remove cables)
- Aerial installation:
  - Installing the cable on poles or towers above the ground as shown in Figure 4.6.
  - Commonly used for overbuilding
  - Usually more affordable than underground installation (depending on the type of poles)
  - Does not require heavy machinery
  - The cable can be lashed to a supporting messenger cable, or self-supporting cables can be used.

For densely populated areas with particular right-of-way challenges, several alternative methods are available such as installation in:

- Grooves cut into pavement
- Drainpipes
- Sewer pipes
- Inside natural gas pipelines

4.1.2 Splice Enclosures, Patch Panels and Fiber Management

Splice enclosures and patch panels can be installed in cabinets or pedestals, on aerial cables, in manholes, etc. The number, type, and placement of the splice enclosures depend on the topology of the network. Figure 4.8 shows two examples of splice enclosure installations.

Splices can be mechanical or fused. Mechanical splices (see Figure 4.10) have the following characteristics:

- Low cost
- High insertion loss (IL) (0.2 dB)
- High backreflection

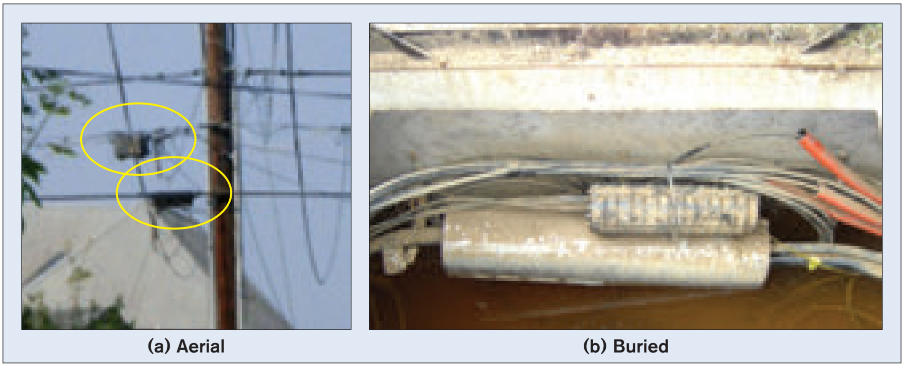


Figure 4.8 – Examples of splice enclosure installation

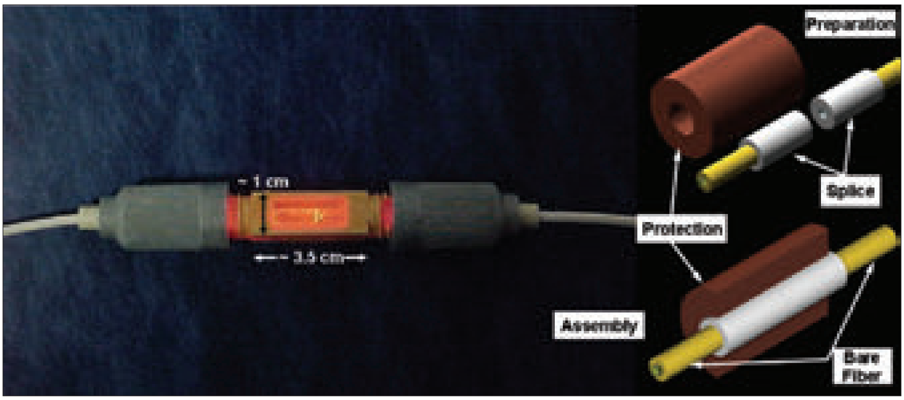


Figure 4.9 – Example of conventional mechanical splicing process

Conventional mechanical splices are considered bulky and not very good in terms of IL and ORL, but they are very handy for quick and inexpensive fiber-to-fiber interconnections. Over the past few years, research has brought new materials and processes that have opened the door to new and improved mechanical splices with much smaller footprints and improved performance, thus closing the performance gap between mechanical and fusion splices. Figure 4.11 illustrates examples of such new mechanical splicing technology and process.

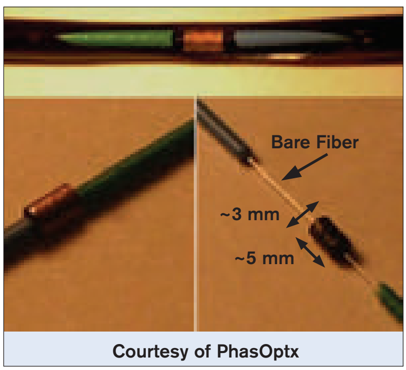


Figure 4.10 – Example of new mechanical splicing technology

Fusion splices have the following characteristics:

- Expensive (requires fusion-splicing equipment – as shown in Figure 3.70 - and knowledgeable operator)
- Very low IL (0.02 dB or better)
- Almost no backreflection

The number of splices depends on the lengths of the cable sections used, typically 2 km or less, 4 km and 6 km. These different cable lengths offer the following advantages and drawbacks:

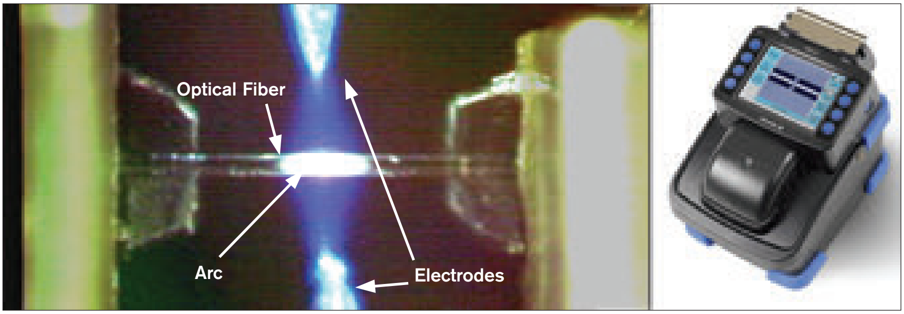


Figure 4.11 – Example of fusion splicing process and equipment

- 2 km lengths or less
  - Typically used for special applications; preferred as drop cables
  - Very easy to maintain
  - Require a large number of splices if used in deployed cables
- 4 km lengths
  - Typically used for deployed cables
  - Relatively easy to maintain
  - Require an average number of splices
- 6 km lengths
  - Could be used
  - Difficult to maintain
  - Require the least amount of splices

Table 4.1 below summarizes the decision process for selecting the most appropriate cable section lengths for various applications in the PON.

Table 4.1 – Value analysis for various lengths of cable sections used in a PON

		Ease of Maintenance	Labor Cost	Number of Splices
		Feeder Cable		
	≤2		Large number of spices = high cost	
	4	Preferred as distance from CO to hub is typically long		
6		Difficult to pull-out fibers	Small number of splices = low cost	
		Distribution Cable		
Length of cable section (km)	≤2	Preferred when distances from hub to drops are short		
	4	Preferred when distances from hub to drops are medium		
	6			
		Drop Cable		
	≤2	Distances from drops to premises are always short		
	4			
	6			

Figure 4.12 illustrates a fiber length and fused splice scenario for a typical topology involving 16 km of feeder cable between the CO and the splitter; there are 3.9 km of distribution cable between the splitter and the drop terminal and 100 m of drop cable between the drop terminal and the ONT. Splices are protected from the environment by splice enclosures.

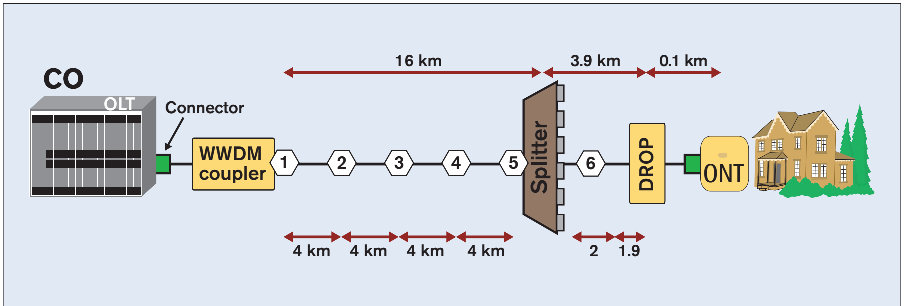


Figure 4.12 – Fiber length and splice scenario for a particular PON deployment

4.1.3 Drop Terminals

Drop terminals can be aerial, underground (mounted in pedestals) or located in apartment buildings, depending on the installation. Drop cables between the splitter and the premises may sometimes be pre-connectorized for quick installation onto the ONUs and can be buried or aerial-mounted. There are various scenarios for drop-cable installation:

- For buried installation:
  - Armored cable – The drop cable may be armored and have sufficient protection to be buried by itself from the drop terminal to the premises. If the cable is preconnectorized, special care must be taken when installing the cable. If the cable is not connectorized, the ONU connector will be installed when the cable will be installed. The connector will come with a small length of cable attached so that the drop-cable fiber can be fusion spliced or mechanically spliced to the connector assembly.

- Ducted cable – Ducts may be buried first between the drop terminal and the premises. The drop cable is then blown through the ducts (with or without preconnections) up to the premises.

— Aerial installation:

- Armored cable – The drop cable will be armored and have sufficient protection to be routed between poles up to the premises. If the cable is preconnectorized, special care must be taken when installing the cable. If the cable is not connectorized, the ONU connector will be installed when the cable will be installed. The connector will come with a small length of cable attached so that the drop-cable fiber can be fusion spliced or mechanically spliced to the connector assembly.

— Mixed installation:

- Buried then aerial – The drop cable may be buried first from the hub to a suitable location, and then proceed with an aerial installation.

- Aerial then buried – The drop cable may be aerially mounted first and then be buried up to the premises.

Many municipalities are currently requiring that, in any new housing development project (Greenfield), any cable installations (electrical, telecommunication, etc.) be buried and that nothing remain visible in the neighborhood, except for pedestals and enclosures. In some cases, there will even be additional requirements to ensure that the enclosures are not visible or that they will simply be buried.

4.1.4 ONT Installation

Figures 4.13 to 4.15 illustrate typical ONT installations at subscriber premises. The fiber is connected to the ONU using a hardened fiber-optic connector, as specified by the Telcordia Technologies Inc. GR 3120 Generic Requirements. This is one of the most critical pieces of hardware after the OLT, the splitter and the drop enclosures.

Figure 4.13 – Typical ONU installation at a subscriber's premises

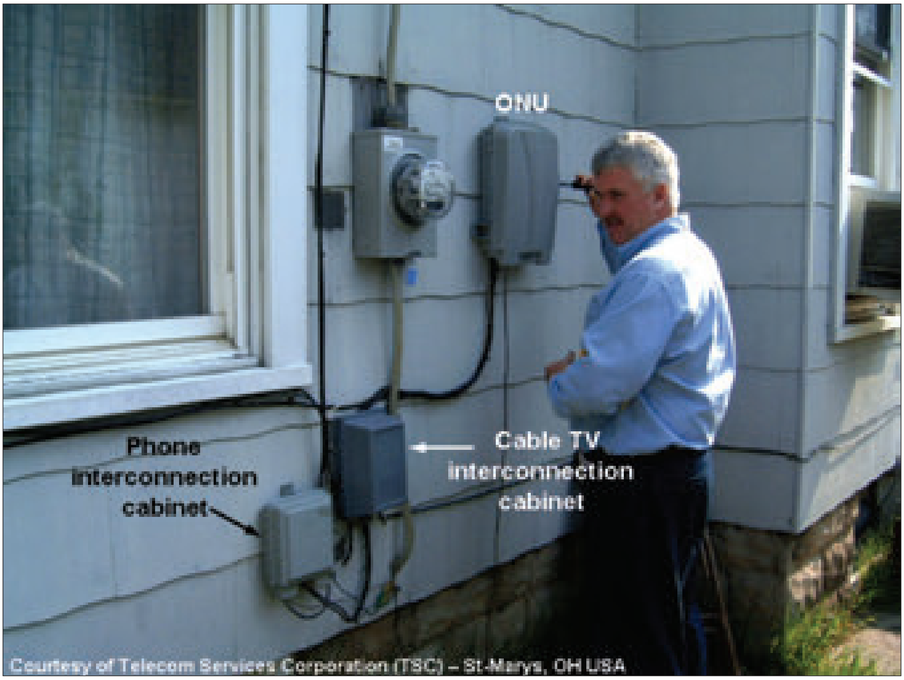


Figure 4.14 – Typical ONT installation completed at the subscriber premises shown in Figure 4.14

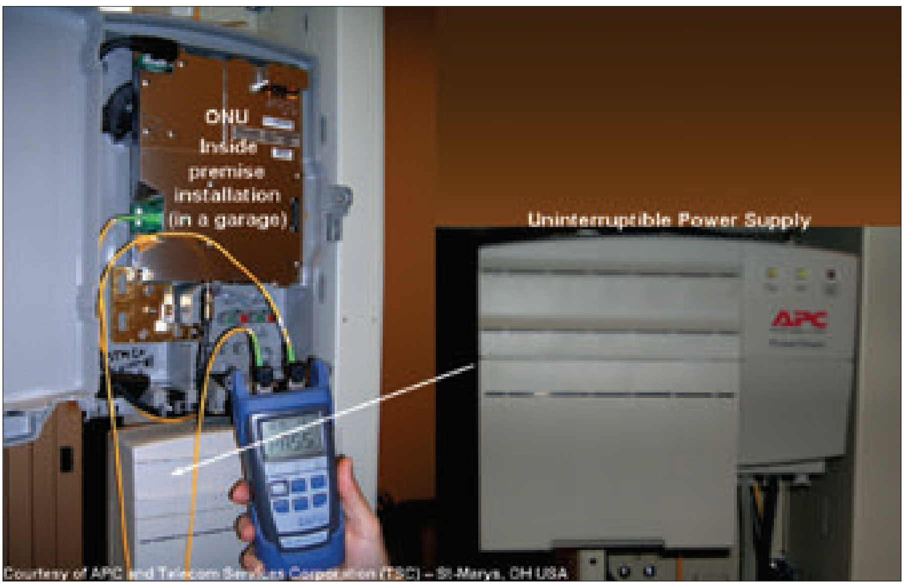


Figure 4.15 – Typical ONU inside-premises installation

Chapter 5

Testing Requirements

5.1 Physical Layer

The purpose of any fiber-optic network is to perform high-speed, error-free data transmission. Adequate testing during network installation will minimize costly and time-consuming troubleshooting efforts by locating questionable splices, dirty or damaged connectors, and other faulty components before they disrupt service.

One of the most important factors in ensuring proper transmission is controlling the power losses in the network against the link's loss budget specifications (see Table 3.1g on page 27). This is done first by establishing a total end-to-end loss budget with a sufficient margin. In addition, backreflections must be reduced to a minimum. This is particularly true for high-power analog video signals from very high power narrowband lasers because strong backreflections will degrade the quality of the video transmission. Finally, several other critical issues, such as chromatic dispersion (CD)[1], polarization mode dispersion (PMD)[2] and non-linear effects (NLE)[3] must be taken into account when applicable.

Optical return loss (ORL) is defined as the ratio of incident power to reflected power and is measured at the input of a device under test (DUT), such as a cable section, a link, or a component. ORL is measured in dB and is a positive number. The higher the ORL value, the better the system will perform.

$$ORL[dB] = 10\log_{10}\left(\frac{\text{Incident Power}}{\text{Reflected Power}}\right)$$

Reflectance, on the other hand, is a negative number and is defined as a measure of the reflection from a single interface or event, such as a transition from a fiber end (glass) to air.

$$Reflectance[dB] = 10\log_{10}\left(\frac{\text{Reflected Power from Specific Interface}}{\text{Incident Power}}\right)$$

Link ORL is made up of Rayleigh backscattering from the fiber core and the reflectance from all the interfaces found along the link. ORL may be a problem in digital DWDM and high-speed transmission systems such as STM-16/OC-48 and STM-64/OC-192 systems, but it is particularly critical for analog transmission, such as the 1550 nm CATV video signals used in FTTH PON. While Rayleigh backscattering is intrinsic to the fiber and cannot be completely eliminated, reflectance is caused by different network elements (mainly connectors and components) with air/glass or glass/glass (with different indices of refraction) interfaces and can always be improved by special care or better designs. To optimize transmission quality, backreflection effects (e.g., light-source signal interference or output power instability) must be kept under control. Therefore, attention must

[1]In a 20 km link Greenfield PON, operating at ≤ 1.25 Gb/s, CD is not an problem. It becomes an issue at high bit rates with FP lasers and/or overbuilt fiber-optic networks.

[2]PMD is an issue for very high bit rates, long links and/or old cable plants.

[3]NLEs are a issue for very-high-power analog overlaid video transmission; long links decrease the NLE threshold.

be focused on ensuring quality network connections through highly accurate ORL measurements. ITU-T Recommendations G.983 and G.984 series allow a minimum link ORL of 32 dB and IEEE 802.3ah allows between 15 to 20 dB (see Table 3.1g on page 27).

The main effects of ORL include the following:

- Strong fluctuations in the laser output power
- Interference at the receiver end
- Lower carrier-to-noise ratio (CNR) in analog systems, which leads to distortions on video signals
- Higher BER in digital systems
- Potential permanent damage to the laser

Figure 5.1 shows typical ORL values for different types of connectors.

Figure 5.1 – Insertion (IL) and optical return loss (ORL) values for various types of connectors

Simplex Connectors							
							
Connector Name	FC	ST	SC	E2000	D4	SMA	BICONIC
Typical IL (not APC) in dB	0.2	0.4	0.2	0.2	0.2	0.25	0.3
Typical ORL in dB	65(APC) 50 (UPC)	50	65(APC) 50 (UPC)		45	30	30
Polishing	SPC/UPC/APC	SPC/UPC	SPC/UPC/APC	SPC/UPC/APC	SPC/UPC	FLAT	FLAT

SPC:Super physical contact/super polished connector
UPC:Ultra physical contact/ultra-polished connector
APC:Angled physical contact/angled polished connector

Adequate loss and backreflection testing is important to ensure that at each transmission wavelength:

- End-to-end loss and backreflection meet the specifications
- Upon questionable results, each segment meets or exceeds the requirements

These tests are critical, especially when the network includes older cables. This is because fibers designed for use at 1550 nm, for instance, may not have been previously qualified for use at 1490 nm and may show higher attenuation than expected.

Note: The ratio of the output power to the input power of a device is called the attenuation and has a positive value of less than one. This parameter is used to characterize the power loss of an optical fiber from end to end. When a device is inserted into an assembly (a network, for instance), the attenuation is called the insertion loss (IL) and has a negative value. This parameter is typically used in *the industry to characterize the power loss of an optical component from input to output. Attenuation may also be used. Both parameters are typically reported in dB units.*

It is especially important that all connectors be properly cleaned and inspected because of the high power levels involved. As singlemode fibers have very small cores, typically 9 to 10 µm in diameter, a single particle of dust or smoke may block a substantial transmission area and increase the loss. When making connections, the following recommendations should be observed:

- Unmated connectors should never be allowed to touch any surface, and a connector ferrule should never be touched for any reason other than cleaning.
- Each connector should be cleaned and inspected using a fiberscope or, better yet, a videoscope after cleaning or prior to mating in the case of PON application. Test equipment connectors should also be cleaned and then inspected (with a fiberscope or preferably a videoscope) every time the instrument is used. Figure 5.2 shows an example of a fiberscope and Figure 5.3 shows an example of a videoscope.

Figure 5.2 – Typical fiberscope

Figure 5.3 – Typical videoscope

- A proper cleaning method and appropriate accessories should always be used. Suitable cleaning accessories would consist of the following (see Figure 5.4):
  - Dry-air blower
  - Cleaning kit (as shown in Figure 5.4)
  - Surface-cleaning pad
  - Tape
  - Optical-quality fabric cleaner
  - Pure alcohol, rated for cleaning fiber-optic components
- Unused connector ports should be capped, and unused caps should be kept in a small plastic bag.

Figure 5.4 – Typical fiber-optic cleaning accessories

When using APC (angled) connectors, special care should be taken when cleaning and connecting them. An APC connector should never be connected to a PC or UPC connector.

WARNING!

- Never look directly into live fibers with the naked eye. Protective eye gear should always be used for inspection.
- Carefully adhere to all human safety procedures.
- Carefully follow all test procedures and safety instructions described in test instrument's user guide.
- Before using a fiberscope, be absolutely sure that the light source has been powered off.
- If possible, use a videoscope to inspect fiber ends and connectors.

- Never look directly into fibers, equipment apertures or connectors unless you are absolutely sure that the light source has been powered off.
- Never power up any equipment using lasers or laser transmitters until you are absolutely sure that all work has been completed on the laser/transmission system and that all cabled fibers are properly cleaned and connected.

5.1.1 Installation

The three main optical tests to be performed during PON installation are:

- Bidirectional ORL measurement
- Bidirectional PON-element optical loss measurement
- Bidirectional end-to-end link characterization

These tests are described in detail below. Each section describes the test setup and the test procedure.

Useful test instruments may include:

- ORL test meter (also referred to as optical continuous-wave reflectometer (OCWR); design schematic shown in Figure 5.5)
- Optical loss test set (OLTS) as shown in Figure 5.6
- Visual fault locator (VFL), used to inject a bright red laser light into the fiber for finding faults, bad splices, breaks and macrobends
- Live fiber detector (LFD), used to detect fibers transmitting traffic
- Optical time-domain reflectometer (OTDR) (see Figure 5.7)
- PON wavelength-isolating power meter (see Figure 5.8) that should be capable of measuring the burst optical power of the ATM or Ethernet traffic, upstream from the ONT

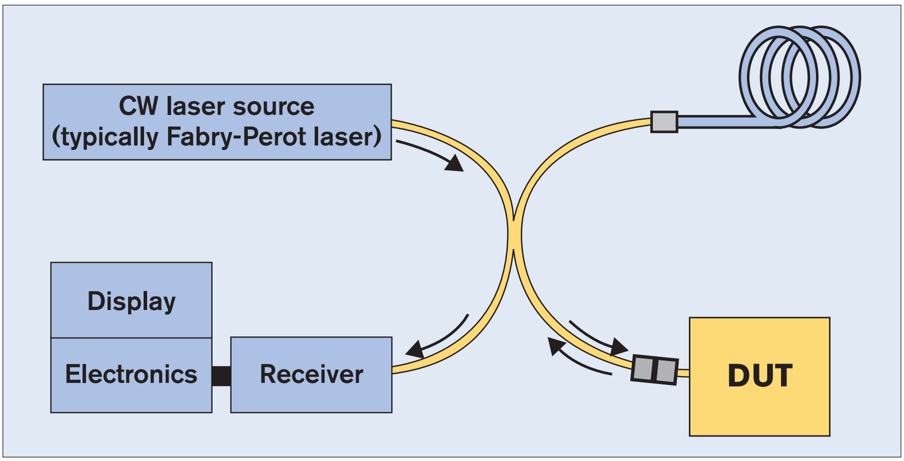


Figure 5.5 – Design schematic of an ORL test meter

Ideally, the PON should be tested right after each element is installed. For instance, end-to-end loss/ORL and OTDR testing should be performed after installing the following segments:

- Between each cabled fiber section
- On the feeder fiber, between the OLT patch panel and each splitter output port (on the output side of fiber distribution hub patch panel)
- Between the fiber distribution hub's patch panel (distribution fiber at the splitter location) and each drop terminal port
- Between the drop terminal port and the OLT patch panel. In this case, the entire link is tested. The test is performed when the output of the splitter is not connectorized but spliced directly to the distribution fiber.
- When the ONT is connected, then the end-to-end link may be tested again, but the typically small length of fiber between the drop and the ONT will not affect the overall link loss very much.

5.1.1.1 Loss Measurement

Because communication over the fiber is bidirectional, the ORL must be measured in both directions. Using an ORL test meter or compatible optical loss test set (OLTS) at each end of the link, the ORL should be measured first in one direction, then in the opposite direction. The OLTS can be used for measuring both ORL and optical loss at the same time.

When using an OLTS, it is important to remember that the test set requires a sequence of two measurements, which are taken in two steps:

1. Two OLTSs are first referenced to each other using their individual light sources.
2. Each OLTS then sends a calibrated power value from its light source over the section under test to the other OLTS, which measures the received power and calculates the loss.

Figure 5.6 – Handheld OLTS for integrated automatic bidirectional ORL, attenuation and distance measurements

The ORL test meter includes a source and an optical power meter to measure reflected power. Some OLTSs, such as the one shown in Figure 5.6, can perform this test, making a dedicated ORL test meter unnecessary. Either one can provide a total end-to-end ORL of components, segments or systems. A typical setup for integrated tests between CO and the drop terminal is shown in Figure 5.9.

Figure 5.7 – Typical OTDR for field measurements

The calibration of the ORL meter should be verified before testing, and recalibration should be performed if required (refer to the user manual supplied with the instrument for complete information).

Before connecting or splicing cables, the ORL should be measured for each section and each splitter branch separately. ORL tests should be performed in both directions. Loss uniformity should be verified between splitter ports. Once all connections are made, end-to-end ORL should be measured between each drop and the OLT.

Figure 5.8 – Typical wavelength-isolating handheld power meter

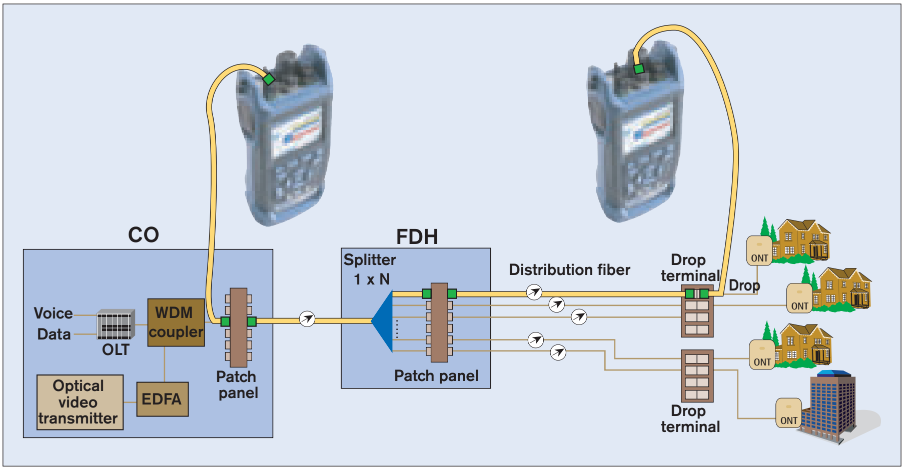


Figure 5.9 – Simultaneous optical loss and ORL measurements

Optical loss is defined as the difference in power level between the transmitting source and the receiving power meter. Insertion loss (IL) is the loss of optical energy resulting from the insertion of a component or device in an optical path.

The total optical system/link loss is the sum of the IL of the following:

- OLT connector
- WWDM coupler
- Splices
- Fiber attenuation
- Splitter
- ONT connector
- Any bad connector mating

When the network is designed, a loss budget is established. This is a detailed analysis designed that helps ensure that the receiver will receive the level of power required for error-free transmission. The loss budget takes into account the transmitter power and the receiver sensitivity, as well as the expected loss of every optical component in the network. The loss budget requirement for the PON, based on ITU-T Rec. G.983, is shown in Table 3.1g on page 27.

The PON splitter causes an inherent loss because the input power is divided between several outputs. Splitter loss depends on the split ratio and is approximately 3 dB for a 1 x 2 splitter. The loss increases by 3 dB each time the number of outputs is doubled. A 1 x 32 splitter has a splitter loss of at least 15 to 18 dB. Table 5.1 shows the loss of a number of split ratios. This loss is seen for both downstream and upstream signals. Splices or connectors at the splitter ports create an additional loss.

Table 5.1 – Typical performance characteristics for different splitter split ratios

	Bit Rate (Mbit/s)	Class[1]	CD	PMD	NLE
Link	622.08	B (10/25 dB) planned	N/A	N/A	Need some margin for SBS and bending (1550 nm)

CD: Chromatic dispersion
PMD: Polarization mode dispersion
NLE: Non-linear effects
SBS: Stimulated Brillouin scattering
[1] In accordance with Table 3-2 data

Figure 5.10 shows the elements in a typical PON that must be taken into consideration when determining the loss budget. This PON has six splices between the OLT and the ONT. An example of a plan for a PON loss budget is shown in Table 5.2.

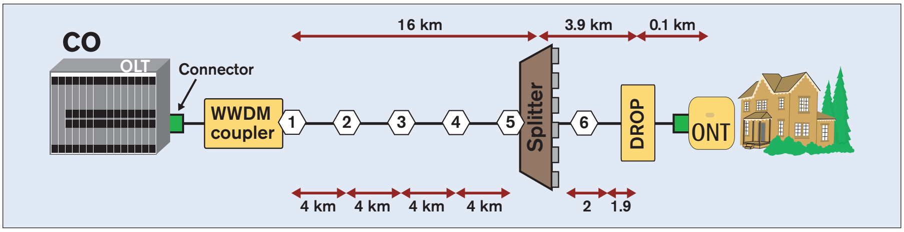


Figure 5.10 -- Planning the loss budget

Table 5.2 – Plan for PON loss budget simulation

Split Ratio	IL[1] (dB)	IL Uniformity (dB)	ORL (dB)	Directivity (dB)	PDL (dB)
1x4	6 - ? 8	? 0.5	? 55	? 55	? 0.2
1x8	9 - ? 11	? 0.8			
1x16	12 - ? 14	? 1.0			
1x32	15 - ? 18	? 1.5			

PDL: Polarization-dependent loss
[1] For both the 1300 band and the 1500 band.

Table 5.3 illustrates the loss budget simulation based on Figure 5.10 and the plan in Table 5.2.

Table 5.3 – Simulation of a PON loss budget

Segment	Loss (dB)	Number/ Length	Total Loss (dB)	Cumulative Loss (dB)	Possible Improvement (dB)	New Cumulative Loss (dB)
WWWDM Coupler 2x1	1	1	1	1	0.7	0.7
Fiber G.652.C 1310 nm (worst case)	0.39 dB/km[1]	20 km	7.8	8.8	0.3/km = 6	6.7
Splices	0.05 dB	6	0.3	9.1	0.3	7
Splitter 1x32	18 dB[2]	1 at 16 km	18	27.1	17	24
Drops	0.1 dB[3]	1 at 19.6 km	0.1	27.2	0.1	24.1
Connectors	0.2 dB[4]	2	0.4	27.6 (Class C)	0.2	24.3 (Class B)

[1] In accordance with Figure 3-10 (worst case)
[2] In accordance with Table 4-1
[3] Margin for bad mating
[4] In accordance with Figure 4-1 data

In this example, no loss from dispersion or any non-linear effects are taken into account (additional1 dB loss would be allowed for very-high-bit-rate systems at 1550/1490 nm). Based on the worst-case cumulative loss of 27.6 dB, this system does not meet the Class B loss budget. The system would then meet Class C (min. 15 dB/max. 30 dB) with a 2.4 dB margin for the maximum budget allowed. Table 5.3 also shows possible improvements that could be made to the PON. The effect of all these improvements would allow the PON to meet the Class B budget (min. 10 dB/max. 25 dB) with a slight margin.

The greatest loss is caused by the splitter and the fiber attenuation in the 1300 nm region. The splitter loss would have to be improved (either by using a lower split ratio or, in the future, using a new approach); otherwise, a less expensive class will not be possible.

Loss can be measured using a separate source and an optical power meter (OPM). A basic OLTS consists of a light source and an OPM, while an advanced OLTS consists of a light source and OPM combined into one unit, which is particularly useful for bidirectional testing, automatic referencing and results analysis. Some of the more advanced OLTSs, as shown in Figure 5.6, can perform automatic bidirectional end-to-end loss and ORL tests together, also providing an estimate of the link distance and chromatic dispersion.

The following considerations are important when selecting an OLTS for PON applications:

- Automated testing reduces testing time and risk of operator errors.
- High dynamic range allows for testing of very lossy components (such as the splitter) and/or increasing distance coverage.
- An integrated talk set facilitates bidirectional communication between technicians performing end-to-end tests.
- Dual- or triple-wavelength (1310/1490/1550 nm) testing capability is essential for testing PONs based on legacy fibers, which exhibit higher attenuation compared to the more recent vintage fiber.

Further information on choosing and using an OLTS can be found in suppliers' white papers and applications notes.

Before connecting or splicing cable fibers, the optical loss should be measured for each cable section and each splitter branch separately. The loss test should be performed in both directions and loss uniformity should always be checked at each of the different splitter ports.

Once all connections are made, the end-to-end loss should be measured between each drop terminal and the OLT. Total loss should not exceed the loss budget; otherwise, error-free transmission may not be possible.

Measurements should always be performed at the output of the patch panel to ensure that the connector mating is taken into account.

To perform automatic loss testing using two OLTSs; four steps are usually required (refer to the user guide supplied with the instrument for detailed information):

1. First, if required, an offset nulling may be performed in order to compensate for detector noise and internal offsets. Some test units do not require this step.
2. Next, the test setup (on both instruments) must be configured. This consists in selecting the appropriate wavelength(s) and establishing other test parameters.
3. Then, referencing (on both instruments) is performed. This is necessary to measure loss through the fiber only, and not through the test jumpers and accessories. Some units automatically perform this step, but for those that don't, two methods are available:
   - The loopback referencing method – This technique must be performed on each OLTS. The loopback reference consists in connecting a test jumper at each unit's source port and looping it back to the same unit's detector port. The measured power level at the detector port is stored as a reference.
   - The side-by-side referencing method – This is a more accurate option, which is performed by connecting the source of unit A to the detector port of unit B and the source of unit B to the detector port of unit A.
4. Finally, the test is initialized (on initializing instrument). Some units automatically perform this step for both instruments.

Once both OLTSs have been referenced, the jumper on each OLTS is disconnected from the detector port and connected to the fiber under test (FUT). The test is initiated on one OLTS. The source of this OLTS sends light through the link. The other OLTS measures the received power values and communicates this information to the initiating instrument, which compares the quantity of light received with the reference measurement. The difference between the two measurements corresponds to the average link loss.

5.1.1.2 Link Characterization

During PON installation, it is important to ensure that each cable section meets or exceeds the cable specifications. This can best be accomplished by using an OTDR. Unlike an OLTS, which characterizes the overall loss of an entire link using two instruments, an OTDR provides a detailed map of the link, allowing the users to locate and characterize every individual element in the link, including connectors, splices, splitters, couplers, and faults.

An OTDR operates by sending a high-power pulse of light down the fiber and measuring the light reflected back. Every event in the link (that is, every optical component and optical fault) causes a reflection or an optical loss, or both (see Figure 5.11). Fiber ends and breaks, as well as connectors and other components, each reflect a small part of the pulse back to the OTDR. The OTDR uses the time it takes the individual reflections to return to determine the distance of each event.

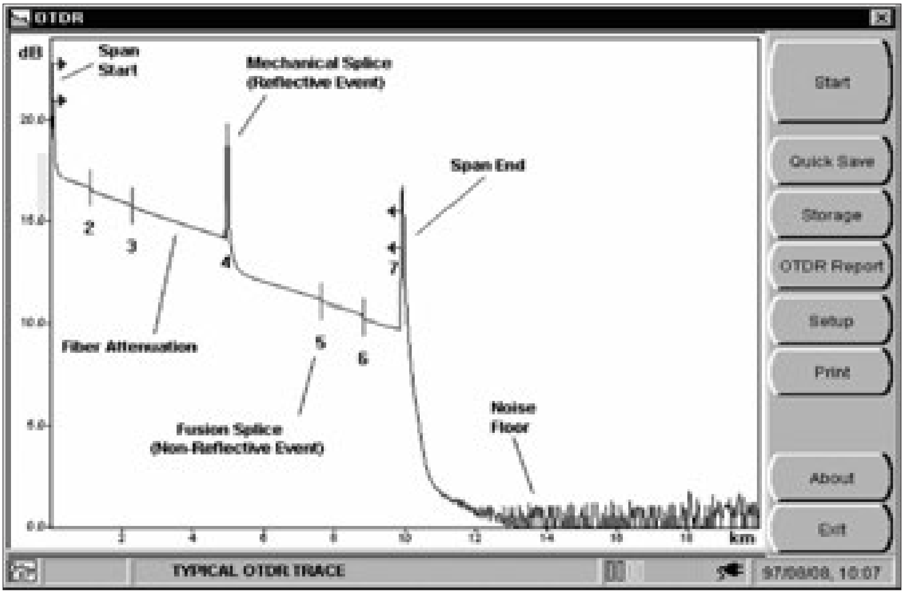


Figure 5.11 -- Example of OTDR test results

Optical fibers uniformly backscatter a small portion of the light over their entire length. The OTDR measures this backscattered light to determine the attenuation of the fiber. Sudden reductions in the level of backscattered light correspond to optical losses due to splices or other events. For instance, the fiber attenuation for new G.652.C fibers can be measured over the ranges of wavelengths used in the PON, typically:

- 0.33 dB/km at 1310 nm (0.39 dB/km for worst case); higher in the 1200 nm region
- 0.21 dB/km at 1490 nm (0.275 dB/km for worst case)
- 0.19 dB/km at 1550 nm (0.25 dB/km for worst case)

Larger spectral attenuations may be observed in older G.652.A fibers.

The faults that can be detected by the OTDR include:

- Fiber misalignment
- Fiber mismatch
- Angular faults
- Dirt on connector ferrules
- Fiber breaks
- Macrobends

Macrobends are unwanted events that are caused when a fiber is bent tighter than its minimum bend radius (tie-wrap too tight, etc.), and they can easily be detected by comparing the loss at 1310, 1490 and 1550 nm. This is because macrobends have more significant losses at longer wavelengths (1550 nm) than at lower ones (1310 nm). The best available OTDR wavelength for macrobending detection is 1625 nm (the longer the wavelength, the better).

Another important consideration when using an OTDR is the dead-zone phenomenon. Because the detector in the OTDR is very sensitive, it may become saturated by strong reflections, such as from the OTDR output connector and from the first event (connector) in the network, if this event is particularly close to the OTDR. Often, the longest dead zone occurs at the first connection (the OTDR bulkhead connector). Since it is impossible to measure loss within a dead zone, loss due to splices and connectors close to the OTDR launch point cannot be determined under ordinary circumstances. However, the use of a pulse suppressor box (PSB) between the OTDR and the FUT can work around this problem. The PSB contains a length of fiber-optic cable that allows the first connector, as well as events hidden by the dead zone, to be included in the link loss measurement. Ideally, the dead zone of the OTDR should be as short as possible. Some recent OTDR models have an event dead zone as short as 1 m and an attenuation dead zone starting at 4 m.

Loss from the last connector of the FUT can be measured in the same way, by connecting the PSB to the last connector. The PSB enables the OTDR to compare backscattering levels before and after the event to calculate the connector loss.

The PON link characterization using an OTDR has created new requirements for OTDRs:

- Much shorter dead zones are required in order to detect the closest drop terminal from an ONT.
- A much larger dynamic range is required to go through the lossy splitter (see Figure 5.12 for an example between a general OTDR and a PON-optimized OTDR).
- The OTDR should be able to measure through the splitter, distinguishing between the splitter loss (approximately 17.5 dB for a 1x32 splitter) and the end of the fiber, in order to characterize the link after the splitter.
- High resolution is required to characterize closely spaced events.

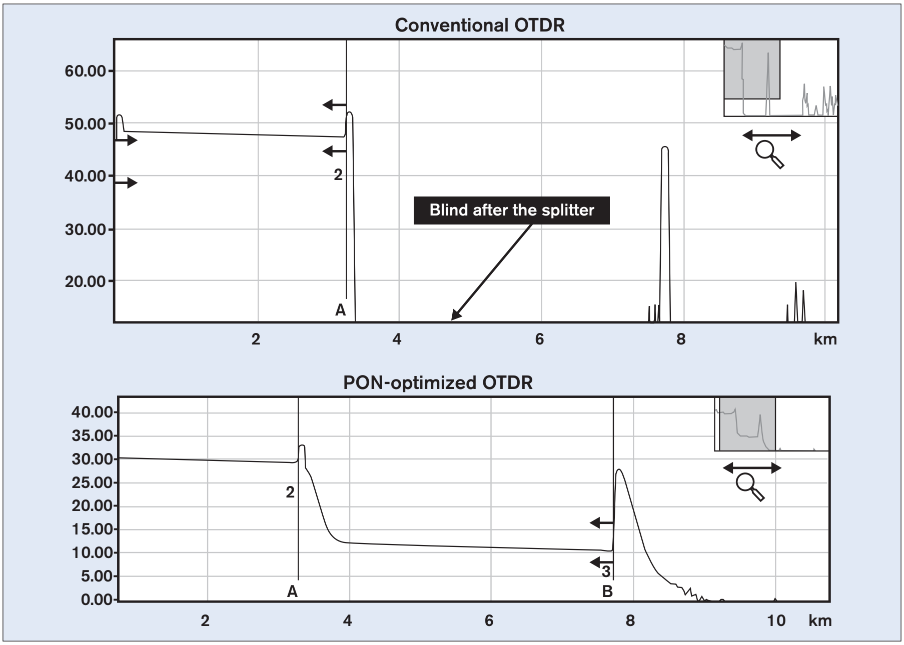


Figure 5.12 – Results from a conventional and a PON-optimized OTDR [P147 from "Testing and Maintaining FTTH PONs: New Challenges" - Stéphane Chabot]

For PON testing, the OTDR should be able to test at three wavelengths (1310, 1490 and 1550 nm) and possibly a fourth one (1625 or 1650 nm for macrobending-sensitive detection). In many cases, however, testing at 1550 nm is considered adequate to cover the 1490-nm region at the same time. It is generally agreed that the fiber attenuation at 1490 nm is approximately 0.02 dB greater than at 1550 nm (see Figure 3 10 on page 30). This is usually true for very recent vintage fiber (late '90s and more recent), especially for the G.652.C low-water-peak fiber. However, this may be questionable for older vintage fiber (early '90s and older) when G.652.C did not yet exist and when little interest was placed on the water peak (1383 nm peak in the E-band). In many cases, the amplitude and the width of the water peak were much larger than what is currently available. Another reason to test both at 1490 nm and 1550 nm is based on the fact that each wavelength carries different critical types of service.

A new type of PON-optimized OTDR uses the 1650 nm wavelength for in-service troubleshooting of PONs. This type of OTDR has a dedicated port for testing at 1650 nm and uses a filter to reject all unwanted signals (1310 nm, 1490 nm and 1550 nm) that could contaminate the OTDR measurement. Only the OTDR signal at 1650 nm is allowed to pass through the filter, generating a precise OTDR measurement. This type of OTDR does not interfere with the CO's transmitter lasers, because the 1650 nm wavelength complies with the ITU-T Recommendation L.41 (Maintenance wavelength on fibers carrying signals). This recommendation suggests a 100 nm difference between the OTDR wavelength used for in-service maintenance and the closest transmission wavelength (1550 nm).

For testing long fibers or lossy components, high dynamic range is necessary, whereas when characterizing a discrete event, a short pulse is often required. These two requirements contradict each other: a longer pulse will provide a larger dynamic range, while a shorter pulse will come with a lower peak power, limiting the dynamic range (see Table 5.4).

Table 5.4 – Contradictory requirements for OTDR performance

Pulse width	Pulse power	Range	Sensitivity	Dynamic range/SNR	Resolution
Long	Large	Long	High	Large	Low
Short	Small	Short	Low	Low	High

Note: Characteristics indicated in green is favorable to PON.

The OTDR analysis software must be well-designed to thoroughly locate all possible types of events, such as:

- Reflections, caused by connectors, fiber breaks or ends
- Losses, caused by splices or macrobends
- Gains, caused by imperfect core alignments or diameter differences (delta variations in mode-field diameter)

A good-quality OTDR should be able to clearly point out all types of events on the trace to make them easily identifiable to the user; it should also provide a list of events in an event table.

It is important to select an option that provides a well-designed, easy-to-use interface and features, such as signal averaging, report generation and printing, as well as an automatic mode of operation. Some OTDRs also include a built-in visual fault locator (VFL).

Further information on choosing and using an OTDR can be found in supplier-s' white papers and applications notes.

Before using an OTDR, it is important to understand the test parameters to be able to test them correctly. Although many OTDRs have an “Auto mode” in which the instrument attempts to determine the optimal settings for the link under test, in some situations, it may be necessary to set the parameters manually in order to obtain the desired results. When testing at several different wavelengths, the same settings for all wavelengths, or different settings for each individual wavelength, may be used. In addition, there are usually options for storing test results in a database and for printing reports. The main test parameters are described below. Refer to the instrument’s user manual for complete information.

- Range (see Table 5.4):
  - Maximum distance at which the OTDR will detect an event
  - Should normally be set to cover the entire length of the link, unless only part of the link is tested at high resolution (short pulse width)
- Pulse width (see Table 5.4):
  - Time width (duration) of the pulse that is sent into the link by the OTDR
  - Long pulses:
    - Travel further down the fiber
    - Improve the signal-to-noise ratio (SNR)
    - Result in less resolution, making it more difficult to separate closely spaced events
    - Result in longer dead zones
  - Short pulse width provides:
    - High resolution
    - Short dead zones
    - Short range
    - Low SNR
  - Generally, it is preferable to:
    - Select the shortest possible pulse width that allows a view of the entire link
    - Make further adjustments for optimization
- Pulse power (see Table 5.4):
  - Large pulse power and consequently large dynamic range are required in FTTH PON testing because of the splitter.
- Acquisition time:
  - Time period during which test results will be averaged
  - Long acquisition times (45 s to 3 min)
  - Produce cleaner traces (especially with long range)
  - Average out more noise
  - Increase SNR
  - Increase the OTDR's ability to detect small and closely spaced events
  - Fully characterize a link with optimal precision
  - Ensure the end-to-end loss budget is respected
  - Short acquisition time (e.g., 10 s) should be used when performing a quick test in order to locate a major fault, such as a break.

- Pass/Warning/Fail criteria:
  - A message is displayed at the end of an analysis to inform the user if one or more events exceed a preset threshold.
  - Separate Warning and Fail thresholds can be set for each type of measurement (splice loss, connector loss, reflectance, fiber section attenuation, total span loss, total span length, and ORL). This feature ensures that each optical component in the link meets its acquired values.

During installation, OTDR testing should be performed after each segment of the network is installed. Each fiber should be tested between the splitter and the OLT at the CO (see Figure 5.13), as well as between the splitter and the ONTs (see Figure 5.14),bidirectionally if possible. Several types of events, such as mismatched core size, generate different levels (gainers vs. losses) depending on whether the light comes from one direction or the other. Bidirectional testing provides more accurate results because the loss values measured in each direction can be averaged. Testing at multiple wavelengths allows for the identification of macrobends.

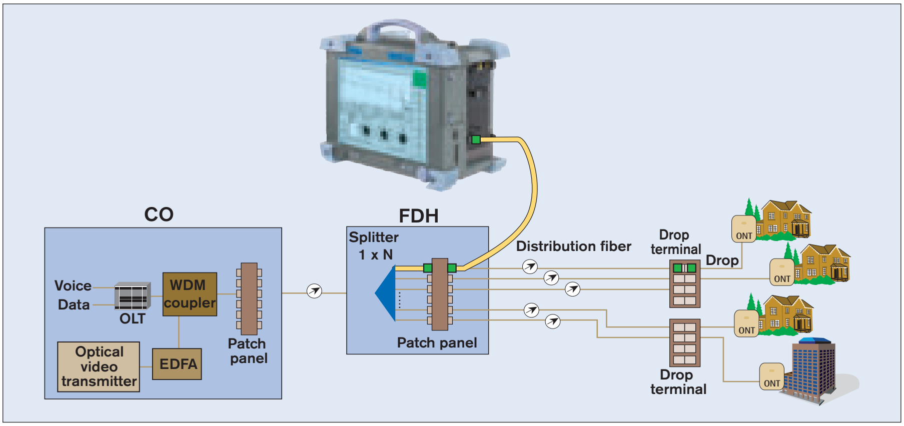


Figure 5.13 -- OTDR test between the FDH and CO

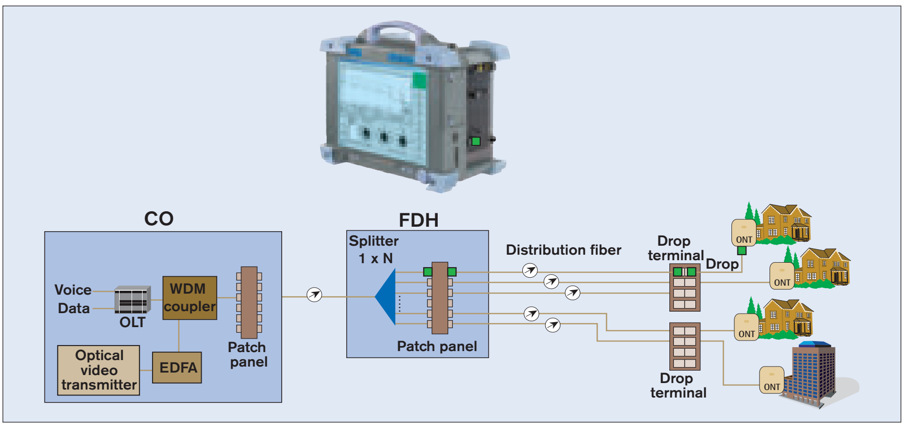


Figure 5.14 – OTDR test between the FDH and one ONT

It is sometimes useful to test from the CO towards the splitter(s) and all the way to the ONTs. However, when many distribution fibers are being tested, the reflection of each of the different fibers will be combined, and the interpretation of the OTDR trace will become more difficult, and maybe even be impossible. Downstream OTDR testing is possible in the following conditions:

- Only one fiber is alive at the splitter output – all the remaining fibers are terminated.
- All the ONTs are at different ranges, each range is known, and an appropriate algorithm is available in the OTDR software to discriminate and analyze the resulting traces.
- Upstream reflectometry is used in each ONT.
- Each ONT has a unique signature making the upstream OTDR pulse selectively reflected.

White papers or application notes on PON testing are provided by some OTDR suppliers.

5.1.2 Service Activation

The following tests should be performed when first activating the network or when connecting an ONT.

5.1.2.1 OLT (initial service activation only)

An optical power measurement at the OLT is required to ensure that sufficient power is delivered to the ONTs. This is done only during the initial activation because it cannot be repeated without interrupting service for the entire network. To perform this measurement, the feeder fiber is disconnected and the power is directly measured at the output of the WWDM coupler. Two methods can be used:

- An OPM measures the total optical power.
  - Optical spectral filters must be used in order to measure the power at each individual wavelength, typically one wavelength at a time.
- A wavelength-isolating PON power meter measures the power of each wavelength simultaneously.
  - Power thresholds can be set in order to provide Pass, Warning or Fail status for each wavelength simultaneously.

After reconnecting the feeder fiber, a similar test is performed at the fiber distribution hub (FDH), measuring the power at each splitter output.

5.1.2.2 Optical network terminals (ONT)

Each time a new ONT is added to the PON, the downstream and upstream optical power at the drop terminal should be measured.

The preferred method is to use a wavelength-isolating PON power meter that can be connected as a pass-through device. An alternate method is to use an optical power meter (OPM) and spectral filters; however, this method does not allow for measurement of the upstream bursty signal, nor pass-through operation.

Figure 5.15 shows a wavelength-isolating PON power meter connected as a pass-through device between the drop port and the ONT. This type of instrument, which is relatively new on the market, simultaneously measures the downstream power at 1550 nm and 1490 nm, and the upstream power at 1310 nm. Unlike an OPM, which measures the average power of an optical signal, the wavelength-isolating PON power meter detects the power of the ATM traffic bursts and provides accurate measurement.

Figure 5.15 – PON ONT pass-through traffic test with a PON-optimized power meter

An experiment was conducted to simulate the upstream bursty traffic and demonstrate the validity of the wavelength-isolating PON power meter. The experimental setup is shown in Figure 5.16. A pattern generator was used to simulate various bit sequences at 1310 nm. Standard and wavelength-isolating PON power meters were connected in parallel for comparison purposes. An oscilloscope was used to observe the various patterns. In one pattern, for example, a single BPON cell of scrambled data (~50% duty cycle) was transmitted every 100 ms (polling period), as shown in Figure 5.17.

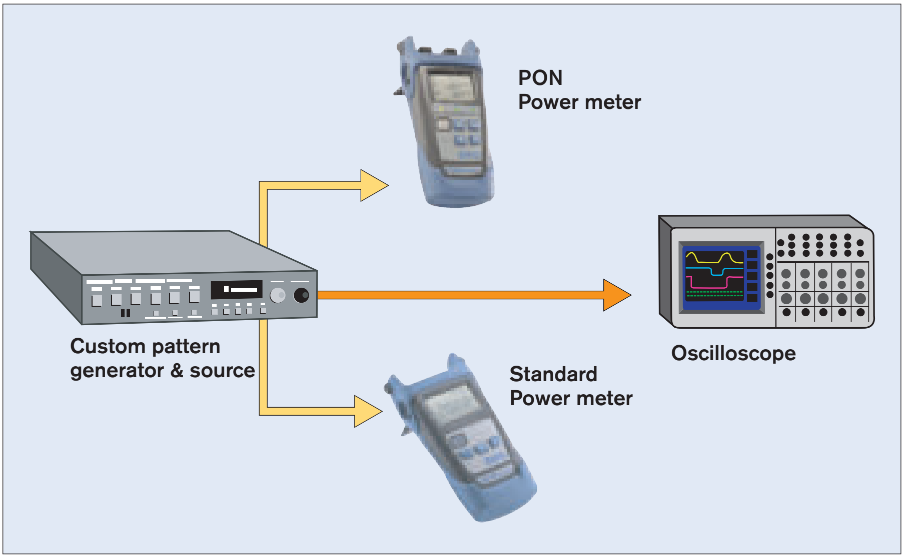


Figure 5.16 – Setup for performance comparison between a standard and a PON-optimized power meter in "bursty" traffic conditions

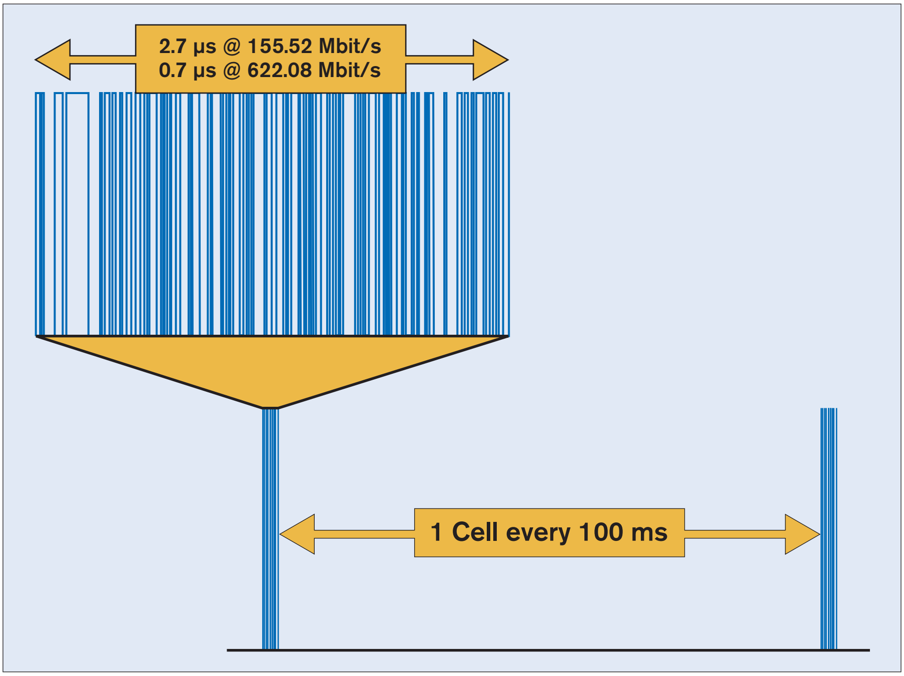


Figure 5.17 – Transmission of one BPON cell every 100 ms

Table 5.5 – Results of power measurement between a standard and PON-optimized power meter

Transmission pattern		Power Measurement Results (dBm)	
		Standard Power Meter	PON-Optimized Power Meter
10-MHz 1010 Continuous Bit Stream		-3.0	-2.9
155 Mbit/s	Long PRBS	-4.8	-2.5
	1 Cell/100ms	-49.9	-3.6
622 Mbit/s	Long PRBS	-5.1	-3.0
	1 Cell/100ms	-55.5	-3.7

It can be seen from the results in Table 5.5 that the standard power meter and the PON power meter give essentially the same results for an alternating 1010 bit stream. However, the measurement of a sparse data pattern cannot be adequately performed with a standard power meter because an average power measurement, without knowing the effective transmission window and its duration, gives results that are much lower than the burst power. A specifically designed power meter that takes this fact into account and measures the source's average power only during its active transmission window is capable of accurately measuring the burst power.

For EPON, the shortest data length is 64 bytes (512 bits). These bytes are scrambled under a duty cycle close to 50% whatever the transmitted signal (4B/5B encoding plus NRZi), At nominal 1000 Mb/s, the physical bits are 0.8 ns wide (physical EPON bit rate of 1.25 Gb/s). So, for the worst case (upstream), the bit pattern will look like the one used in the previous example (Rec. G.983.x ATM cell of 53 bytes (424 bits for 680 ns at 622 Mb/s), but the effective length of the EPON signal will be 410 ns instead of 680 ns.

Tests have been done based on the previous hypotheses:

1. For ONT power ≥ −10 dBm, there are negligible difference (< 0.1dB, inside the PON-optimized power meter) between the BPON and EPON case.
2. For ONT < −10 dBm, for measurements done on the CO side of the splitter (near the OLT), a difference of the order of 1 dB can be observed between the two tests, based on the use of two different filters for both power ranges.

For GPON, an upstream signal of 1244.16 Mb/s (53 bytes ATM) has been used for burst testing. The same negligible difference is observed for the first power range case (same worst case as for one cell), this time of 0.5 dB. For the next power range, the difference is greater than 1 dB. It is useful to note, however, that in ITU-T Rec. G.984.2, the ONU emits at launch power > −6 dBm for 622 Mb/s and at > −3 dBm for 1244.16 Mb/s (4 dB less is tolerated if the OLT uses a APD-based receiver). Consequently, the first power range is still applicable and the PON-optimized power meter can therefore be used to measure burst power in BPON, EPON and GPON.

The downstream power at 1550 nm and 1490 nm must meet the minimum ONT receiver sensitivity (depending on the PON class). The upstream power should correspond to the ONT specifications. If the optical power level is insufficient, troubleshooting must be performed. Similarly, the upstream power at 1310 nm must meet minimum criteria to be properly detected at the OLT. Knowing the worst-case optical power budget makes it relatively simple to establish the signal's minimum required optical power value that the 1310 nm signal must have right at the ONT output.

When all problems have been corrected and the measured power level at the drop terminal is sufficient, the drop terminal may then be directly connected to the ONT.

Note: It is crucial to understand that the 1310 nm signal transmitted upstream by the ONT is, by nature, a burst, and is not continuous. For this reason, the power of the traffic from the ONT must be detected with the appropriate instrumentation and not with common instruments used to detect continuous power.

5.1.3 Troubleshooting

Troubleshooting a PON involves locating and identifying the source of an optical problem in what may be a complex topology that includes several elements, as shown in Figure 5.18. The numbers indicate the different zones where a problem may be located.

Table 5.6 shows how noting which ONTs are affected can help locate the problem.

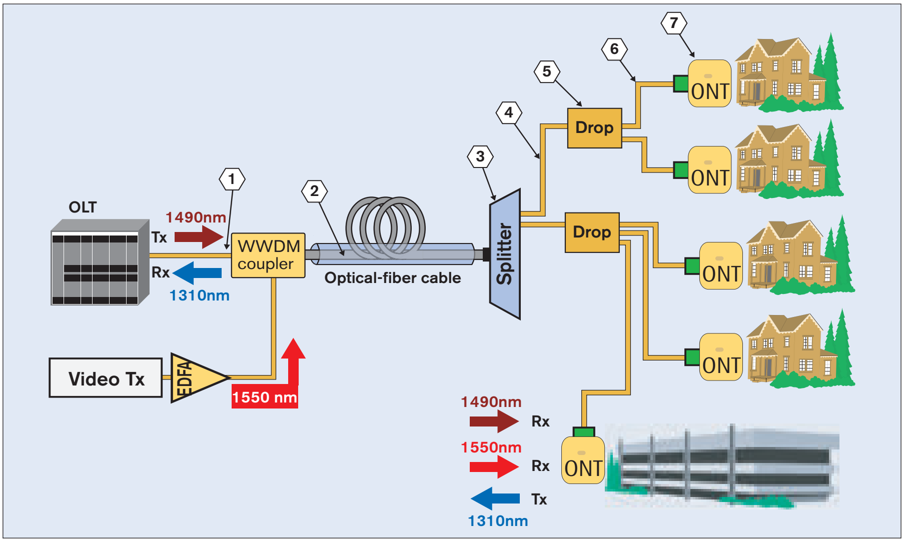


Figure 5.18 – Example of potential problem-causing locations in a complex PON topology

Table 5.6 – Locating a problem in a typical FTTH PON

Affected ONTs	Possible problem locations
All ONTs or several ONTs (the most distant ones) throughout the network	In the CO (zone 1)
	Along the feeder fiber (zone 2)
	At the main FDH (zone 3)
All ONTs or several ONTs (the most distant ones) in one branch	At the main FDH (zone 3)
	Along the intermediate cable (zone 4)
	At a drop (zone 5)
One ONT	At the last drop (zone 5)
	Along one drop fiber (zone 6)
	At drop terminal, along the drop, or at the ONT (zone 7)

If a break occurs in the cable between the OLT and a downstream splitter, all downstream ONTs from that splitter will be affected. However, if a problem such as macrobending or dirty connectors causes optical power to be lost somewhere in the network, only some downstream ONTs may be affected. Because the attenuation in fiber-optic cables is proportional to length, distant ONTs will receive a weaker downstream optical signal than the closer ones. The upstream optical signals received at the CO from the more distant ONTs are also weaker and the OLT will detect such decreased performance.

The problems that may occur in an FTTH PON include:

- Optical power level at one or more ONTs does not meet the specified minimum power level
- Loss of signal (no power)
- Increased BER or degraded signal (may be due to insufficient power)
- Hardware problem with an active component (at ONT or CO)

Because most of the components in the network are passive, problems are usually due to dirty, damaged or misaligned connectors,, breaks or macrobends in the fiber-optical cable. These will affect one, some, or all subscribers on the network, depending on the location of the problem.

Most problems can be located using the following equipment:

- Wavelength-isolating PON power meter – has the following characteristics:
  - Connects as a pass-through device, allowing both downstream and upstream traffic to travel unimpeded.
  - Measures the power at each wavelength simultaneously.
  - Detects the burst power of the traffic.
  - Can be used for troubleshooting at any point in the network (see Figure 5.19).

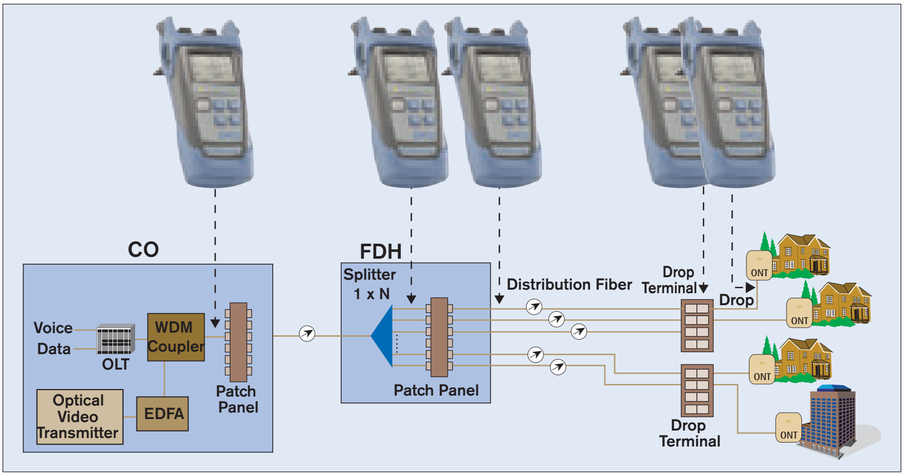


Figure 5.19 – Using a PON wavelength-isolating power meter for troubleshooting

- OPM integrated with spectral filters – has the following characteristics:
  - Measures power at specific wavelengths, one at a time
  - Measures continuous power, but not the burst power of traffic from the ONT
  - Cannot be connected as a pass-through device
- VFL – has the following characteristics:
  - Injects a bright red laser light into the fiber
  - Finds faults, making some bad splices, breaks and macrobends visible to the naked eye; these which would be impossible to find locate otherwise
  - May be built into an OTDR
- OTDR – has the following characteristics:
  - Provides graphical traces allowing for the location and characterization of every element in a link, including connectors, splices, splitters, couplers, and faults

- LFD with interchangeable adapter heads – has the following characteristics:
  - Detects traffic
  - Measures signal strength anywhere on along fiber without having to disconnect them

The interchangeable adapter heads allows for testing of different fiber types.

Table 5.7 to Table 5.9 present typical troubleshooting procedures for different situations. See also [2].

5.2 Protocol Layer

5.2.1 ATM Service Activation and Provisioning

One of the advantages of using ATM in PONs is that ATM includes management features to guarantee quality of service (QoS). This allows network service providers (NSPs) to guarantee error free transmissions to their customers.

An ATM service is often governed by the terms of a service-level agreement (SLA). Both NSPs and content providers are interested in knowing how well the service will conform to the SLA.

An SLA is a legal contract between a service provider and a customer that specifies a required level of service. Respecting SLAs can be a way for service providers to attract and retain customers, while sub-standard service can be synonymous with various penalties such as:

- Poor customer satisfaction
- Increased spending on maintenance
- Often, direct financial penalties

SLAs typically specify:

- Maximum downtime
- Mean time to repair (MTTR) when outages occur
- Minimum performance criteria

Two types of QoS testing can be performed on ATM-based PONs similar to other network types:

- Non-intrusive testing (in-service) used to monitor live traffic for service-affecting faults
- Intrusive testing (out-of-service) used for circuit turn-up and troubleshooting faults

The ATM-based PON service provider must verify the QoS of ATM connections to verify that the PON is delivering the QoS that customers are expecting. An end-to-end QoS test can be run in order to determine if performance will degrade over time. If so, the NSP will take necessary corrective actions, including equipment upgrades, to improve service.

Table 5.7 – PON troubleshooting – Any ONT: Malfunction

Any ONT: Malfunction						
Problem	Effect	Possible Cause	Troubleshooting			
			Location	Steps	If	Do
Malfunction	Low optical power level	Dirty/damaged connectors	Drop terminal output	Measure optical power	Dirty connector	Clean connector
					Damaged connector	Replace connector
		Excessive macrobends after last splitter	Last splitter	Test for macrobending	Excessive macrobending	Allow larger bend radius
				Inspect connectors	Dirty connector	Clean connector
					Damaged connector	Replace connector
			Drop terminal	Test for macrobending	Excessive macrobending	Allow larger bend radius
				Inspect connectors	Dirty connector	Clean connector
					Damaged connector	Replace connector
			At last splitter output	Test for macrobending	Excessive macrobending	Allow larger bend radius
				Inspect connectors	Dirty connector	Clean connector
					Damaged connector	Replace connector
	Optical power level OK	ONT hardware problem	ONT	Refer to manufacturer's troubleshooting procedure	Problem found	Correct problem

Table 5.8– PON troubleshooting – Any ONT: Other problems

Problem	Optical PowerEffect	Possible Cause	Troubleshooting: Location	Troubleshooting: Steps	Troubleshooting: If	Troubleshooting: Do
Out of function	No optical power	Fiber break after last splitter (in distribution fiber or drop cable)	ONT	Measure output optical power to confirm there is no signal	No optical signal	Repair ONT
			Drop terminal	Test drop cable from ONT or from drop terminal using VFL or OTDR	Optical signal present	Correct problem in drop cable
				Test distribution fiber from drop terminal using OTDR	Optical signal not present	Correct problem in distribution fiber
BER increase	Insufficient optical power	ONT hardware problem	ONT	Perform steps above as necessary	Problem found	Correct problem
				Refer to manufacturer's troubleshooting procedure		

Table 5.9– PON troubleshooting – Some or all ONTs

Problem	Optical PowerEffect	Possible Cause	Troubleshooting: Location	Troubleshooting: Steps	Troubleshooting: If	Troubleshooting: Do
Some or all ONTs (one splitter) Malfunction	Low optical power level	Excessive macrobends before splitter	Inside and outside FDH	Test for macrobending	Excessive macrobending	Allow larger bend radius
		Dirty/damaged connectors	At splitter	Inspect connectors	Dirty connector	Clean connector
					Damaged connector	Replace connector
All ONTs (one splitter) Out of function repair problem	No optical power	Fiber break before last splitter	Feeder fiber (or fiber between splitters in the case of multisplitter link)	Test feeder fiber with OTDR from ONT, drop terminal, or splitter	Find break	Repair break
		Break in feeder fiber, or problem at CO	From FDH or CO	Test feeder fiber with OTDR		
			OLT output	Measure optical power	OLT out	Repair OLT
			Before WWDM coupler	Measure optical power	Video signal out	Find and
				of video signal		
			WWDM coupler output	Measure optical power	Coupler out	Repair coupler

There are two levels to ATM testing. The first is cell-level testing, which requires wire-speed ATM traffic generation and cell analysis. The second is packet-level analysis, which requires reassembly of cells into packets and analysis of the upper-layer protocol layers. The packet latency and loss measurement is an example of the latter.

5.2.1.1 ATM Performance Parameters

The ATM performance parameters are defined in ITU-T Recommendation I.356 (10/96) – B-ISDN ATM layer cell transfer performance. Typical ATM QoS parameters are:

- Cell error ratio (CER): The number of error cells between two measurement points. An error cell is defined as a cell that contains an error in the Header Error Check (HEC) or in the cell's payload (see Figure 3.34 on page 60).
- Cell loss ratio (CLR): The number of cells that are lost between two measurement points.
- Cell miss-sequence ratio (CMR): The number of cells that are miss-sequenced between two measurement points.
- Cell miss-insertion rate (CMR): The total number of miss-inserted cells observed during a specified time interval, divided by the interval duration. A miss-inserted cell is a cell that appears on a channel incorrectly, mistakenly placed there by the network equipment.
- Severely errored seconds (SES): The period of time during which the sum of the errors, miss-sequenced cells and lost cells has exceeded a user-defined time threshold.
- Cell transfer delay (CTD): A raw delay measurement that measures how much time is required for each cell to travel from one point to another.
- 1-pt cell delay variation (CDV): The measurement of the arrival time of each cell on a particular channel against the expected arrival time for that cell. This passive measurement is defined only for constant bit rate (CBR) traffic. It is performed at a single measurement location without affecting traffic.
- 2-pt CDV: The comparison between the actual cell transfer delay and a reference point or expected cell delay. The expected cell delay is determined at the beginning of the test by sending out a test cell and monitoring how long it takes to arrive at the measurement point. The data shows how many cells were early or late relative to that reference delay, using two measurement points.

5.2.1.2 ATM QoS Testing

When used together, an internetworking analyzer and a tester provide end-to-end ATM QoS testing across a BPON. The test applies to an out-of-service QoS test by measuring the performance of the BPON when transmitting cells back-to-back from one point to another. The configuration can be set in order to perform loopback testing.

Since the signals that cross a network require clock synchronization, network components must extract the clock signal from the received data stream. Jitter on the extracted clock has a direct effect on how well the components can send and receive bits.

Eye diagrams (see Figure 5 20) show the effects of clock jitter. The hexagon in the center (the eye mask) indicates the acceptable eye opening for an optical signal.

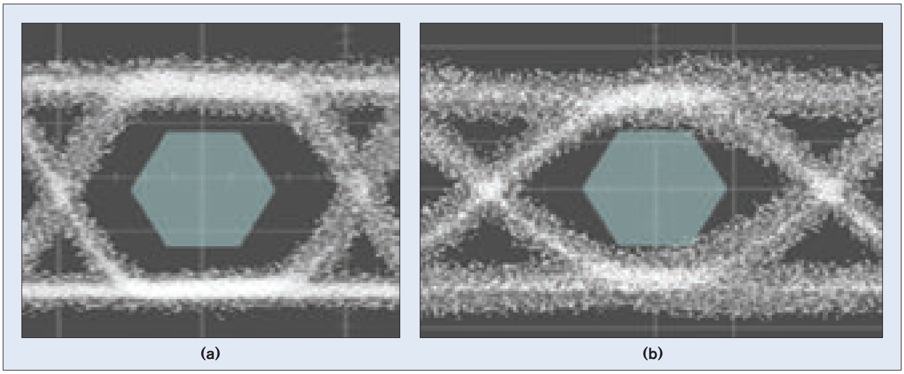


Figure 5.20 – Example of an eye pattern with hexagonal eye mask

When more clock jitter is present in a data stream, the scope traces will appear wider, resulting in a smaller eye opening — one that is closer to the mask limit. If the waveform infringes on the mask, then a receiver may interpret a bit incorrectly or lose clock synchronization. Once a network component can send and receive bits within specifications, BER tests can be performed.

After the integrity of the waveforms has been proven and acceptable BER demonstrated, structured bits can be tested. Layer 2 (data link layer) protocols such as ATM order the bits by placing them into cells. Testing at Layer 2 involves protocol analysis.

ATM test equipment should verify that a CBR) quality is assignedto voice and video traffic while data can use variable bit rate (VBR) quality as part of the QoS agreements. Cell delay variation indicates how much an ATM network component stresses other ATM network components. ATM network emulators allow for the injection of cell errors. The results in the IP layer will show how many IP frames get corrupted as a result. Note that if an ATM cell carrying a fragment of an IP packet is corrupted or dropped, the entire IP packet must be retransmitted, even if the ATM cells containing the remaining fragments were received correctly.

Parameters such as framing errors and severely errored seconds (SES) must also be tested. Noise can be injected into the system to test the system's ability to recover from errors.

When testing at the application layer, enough voice, video, and data traffic must be generated to fully test the network. When voice transmissions and the protocols that carry them are tested, audio quality must be tested.

To ensure correct operation of the network, the physical-layer operation, cell-layer operation and performance, as well as ATM adaptation layer AAL-2 and AAL-5 segmentation and reassembly (SAR) must be tested. Physical-layer testing includes transmitting and receiving physical-layer frames and verifying that errors and alarms are handled correctly. ATM-layer testing verifies that cells are correctly formatted and switched according to their headers. ATM performance measurements include:

- Cell loss
- Cell miss-insertion
- Cell error rate

ATM traffic management mechanisms, such as cell tagging and policing, must also be verified. Adaptation-layer performance measurements include AAL-2 and AAL-5:

- Packet loss
- Error rate
- Delay
- Delay variation

Traffic management mechanisms such as early packet discard (EPD) and partial packet discard (PPD) at the AAL-5 layer should also be thoroughly verified.

Before continuing to other test stages, tests must be performed to ensure that the transport layer behaves reliably and consistently under various conditions (particularly port and back-plane congestion). Otherwise, unpredictable behavior at the higher protocol layers may result.

Table 5.10 summarizes the tests and measurements that need to be performed in the BON.

Table 5.10 – Verification and testing

Transport layer	Protocol	Basic Connection	Advanced connection	Load generation
Framing, alarms, etc.	Correct implementation	Single voice and/or data channel function	System level operation	Operation under realistic and extreme conditions
			Multiple simultaneous channels (including video)	
ATM and AAL functional performance	PDU formats and state machine operation		Mixture of signaling and data	Load generation of signaling and data

Protocol verification requires systematically testing each sublayer of the protocol stack for both control-plane and user-plane functions. This involves verifying the behavior of the transmit side, the receive side and the overall message exchange sequences. Transmit-side monitoring ensures that all protocol data units (PDUs) are correctly formed.

Receive-side testing verifies that PDUs are interpreted correctly, and that out-of-range values and incorrectly formed PDUs are handled in a predictable fashion. State transitions should be monitored to verify behavior under normal and fault conditions (e.g. out-of-sequence messages).

5.2.2 EPON Service Activation and Provisioning

5.2.2.1 Quality and Performance

Legacy transport technologies used in carrier networks, such as ATM, were designed to be able to guarantee measurable QoS. This allowed service providers to establish service-level agreements (SLAs) with their customers.

Unfortunately, Ethernet was not designed with QoS in mind and, originally, offered no means to differentiate between low- and high-priority data. This made it difficult to combine different types of services, such as email and voice communications, over the same link while ensuring that transfer rates met pre-established criteria. Various solutions have been proposed to overcome this shortcoming.

One improvement is to manage network traffic by grouping similar types of traffic together (for example, e-mail, streaming video, voice, large document file transfer) and treating each type as a class with its own level of service priority. This technique is called class of service (CoS). CoS is a queuing discipline, whereas QoS uses a wider range of techniques to manage bandwidth and network resources. CoS examines packet parameters or CoS markings in order to classify packets and place them in queues of different priorities (see Figure 3.67). Unlike QoS traffic management, CoS technologies do not guarantee a level of service in terms of bandwidth and delivery time; they offer a "best-effort" for each class. On the other hand, CoS technologies are simpler to manage and more scalable in terms of network growth, structure and traffic volume.

The three main CoS technologies are:

- 802.1p Layer 2 tagging
- Type of service (ToS)
- Differentiated services (DiffServ)

The first two make use of three bits in the Layer 2 packet header that can be used to specify eight levels of priority. DiffServ, on the other hand, uses more complex policies to determine how to forward a given network packet and offers 64 possible forwarding behaviors, known as per-hop behaviors (PHBs).

Regardless of the CoS specified for any particular type of data, various factors such as network congestion can affect the actual rate at which the data is transferred. For this reason, specific tests are required to verify Ethernet performance in order to ensure that the SLA requirements are met.

5.2.2.2 Ethernet Performance Verification

The data-communication industry has put together a test methodology to address the issues of performance verification at the Layer 2 and Layer 3. The Internet Engineering Task Force (IETF) has developed RFC 2544 [3] in order to specify the requirements and procedures for testing the following performance characteristics:

- Performance availability (throughput)
- Transmission delay (latency)
- Link burstability (back-to-back frames)
- Service integrity (frame loss)

When these measurements are performed, they provide a baseline for service providers to define SLAs with their customers. These measurements become the reference. They enable service providers to validate the delivered QoS and can provide them with a tool to create value-added services that can be tested and demonstrated to customers. For example, these tests provide performance statistics and commissioning verification for:

- Virtual LAN (VLAN)
- Virtual private networks (VPN)
- Transparent LAN services (TLS)
- All using Ethernet as an access technology

The SLA criteria defined in RFC 2544 can be precisely measured using specialized test instruments. The performance verification is usually done at the end of the installation. The measurements are taken out-of-service to make sure that all parameters are controlled.

5.2.2.3 RFC 2544 Tests

The following sections describe each of the RFC 2544 tests. The test equipment used should be able to generate and analyze traffic for EPON (1000BASE-PX10 and -PX20) but also for the following full-duplex networks:

- 10/100/1000BASE-T
- 1000BASE-SX
- 1000BASE-LX
- 1000BASE-ZX

RFC 2544 tests are performed at all frame sizes in order to test transparent connectivity delivered via:

- ATM
- Frame relay
- Next-Generation SONET/SDH
- SONET/SDH hybrid multiplexers
- Ethernet
- VLANs
- Dark fiber
- WDM

The instruments should be capable of transmitting at full-line rate in order to allow the provider to certify that the circuit is efficient and error-free at 100% utilization.

Some test instruments allow automated testing, which help to ensure repeatable results. Automation also provides ease of use for technicians in the field by enabling accurate, efficient measurements and providing reports they can give to customers for future reference.

5.2.2.4 Throughput

Throughput is the maximum rate at which none of the offered frames are dropped by the network under test (NUT). For example, the throughput test (Figure 5.21) can be used to measure the rate-limiting capability. The throughput is equivalent to the bandwidth.

The throughput test allows vendors to report a single value, which has proven to be useful in the marketplace. Since even the loss of one frame in a data stream can cause significant delays while waiting for the higher-level protocols to time out, it is useful to know the actual maximum data rate that the device can support. Measurements should be taken over an assortment of frame sizes. Separate measurements should be taken for routed and bridged data in those devices that can support both. If there is a checksum in the received frame, full checksum processing must be done.

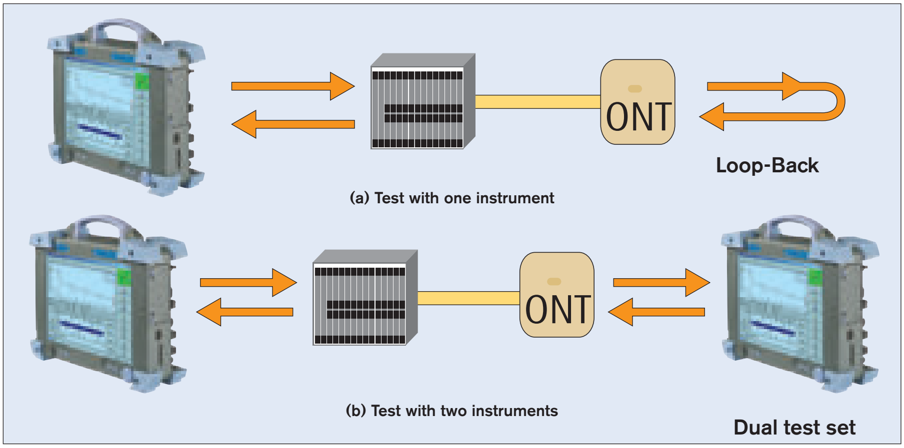


Figure 5.21 – Measuring throughput

The following are issues that will affect throughput test results:

- Single path vs. aggregate
- Load
- Unidirectional vs. bidirectional testing
- Checksum processing required on some protocols
- Packet size

Throughput test procedure :

- Send a specific number of frames at a specific rate through the NUT and then count the frames that are transmitted by the NUT.
- If the count of offered frames is equal to the count of received frames, the rate of the offered stream is raised and the test rerun.
- If fewer frames are received than were transmitted, the rate of the offered stream is reduced and the test is rerun.

[1] *All test procedures are from RFC 2544 [3].*

- The throughput is the fastest rate at which the count of test frames transmitted by the NUT is equal to the number of test frames sent to it by the test equipment.

5.2.2.5 Burst (back-to-back)

In this test (Figure 5.22), fixed length frames are presented at a rate such that there is the minimum legal separation for a given medium between frames over a short to medium period of time, starting from an idle state. The back-to-back value is the number of frames in the longest burst that the NUT will handle without the loss of any frames.

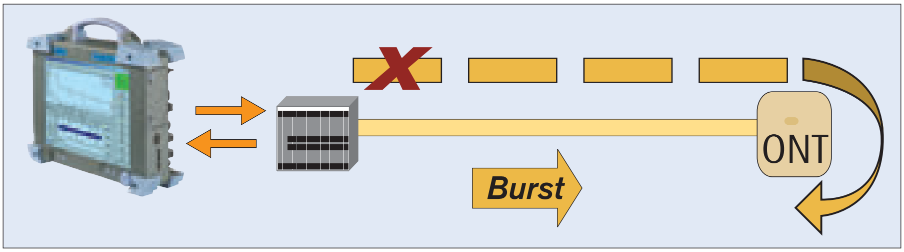


Figure 5.22 – Back-to-back test

Burst test procedure:

- Send a burst of frames with minimum inter-frame gaps to the NUT and count the number of frames forwarded by the NUT.
- If the count of transmitted frames is equal to the number of frames forwarded the length of the burst is increased and the test is rerun.
- If the number of forwarded frames is less than the number transmitted, the length of the burst is reduced and the test is rerun.
- The back-to-back value is the number of frames in the longest burst that the NUT will handle without the loss of any frames.
- The trial length must be at least 2 s and should be repeated at least 50 times with the average of the recorded values being reported.

5.2.2.6 Frame Loss

Frame loss is the percentage of frames that should have been forwarded by a network device under steady state (constant) loads that were not forwarded due to lack of resources. This measurement, as shown in Figure 5.23, can be used in reporting the performance of a network device in an overloaded state. This can be a useful indication of how a device would perform under pathological network conditions such as broadcast storms.

Frame loss test procedure:

- Send a specific number of frames at a specific rate through the NUT to be tested and count the frames that are transmitted by the NUT.

The frame loss at a particular line rate is calculated using the following equation:

- $\text{Frame loss} = \frac{\text{Transmitted frames} - \text{Received frames}}{\text{Transmitted frames}} \times 100\%$
- Measurements should be taken for different frame sizes.

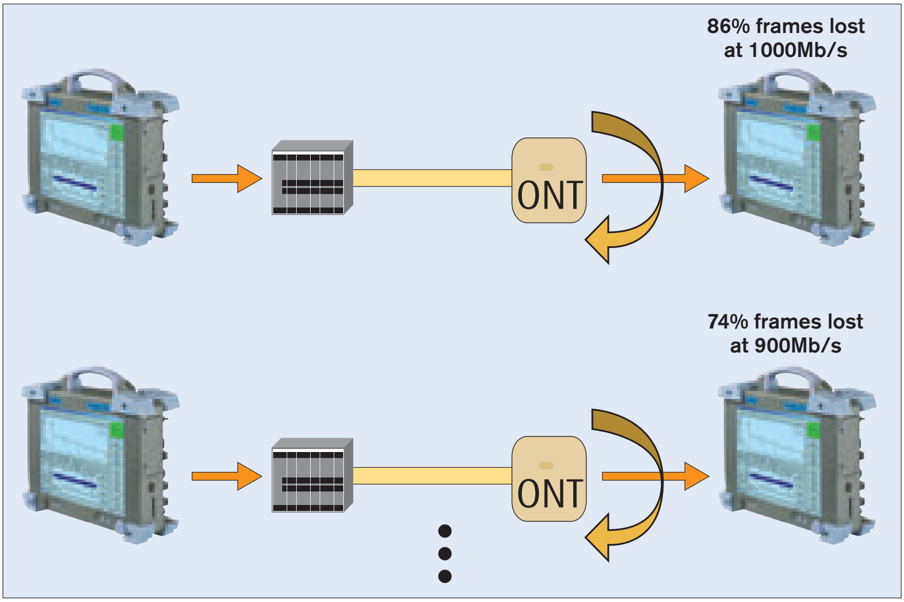


Figure 5.23 – Frame loss test

5.2.2.7 Latency

For store and forward devices, latency is the time interval starting when the last bit of the input frame reaches the input port and ending when the first bit of the output frame is seen on the output port. Round-trip latency is the time it takes for a frame to come back to its starting point. Variability of latency can be a problem. With protocols like VoIP, a variable or long latency can cause degradation in voice quality.

Figure 5.24 shows the configuration for round-trip latency test.

Latency test procedure:

- Determine the throughput of the NUT for each frame size.
- Send a stream of frames at a particular frame size through the NUT at the determined throughput rate to a specific destination.
- Send a tagged frame after 60 s and store timestamp (A). Capture tag frame on reception side and store timestamp (B). The timestamp concept is shown in Figure 3.63.
- The latency is timestamp B minus timestamp A.
- The test must be repeated at least 20 times with the reported value being the average of the recorded values.

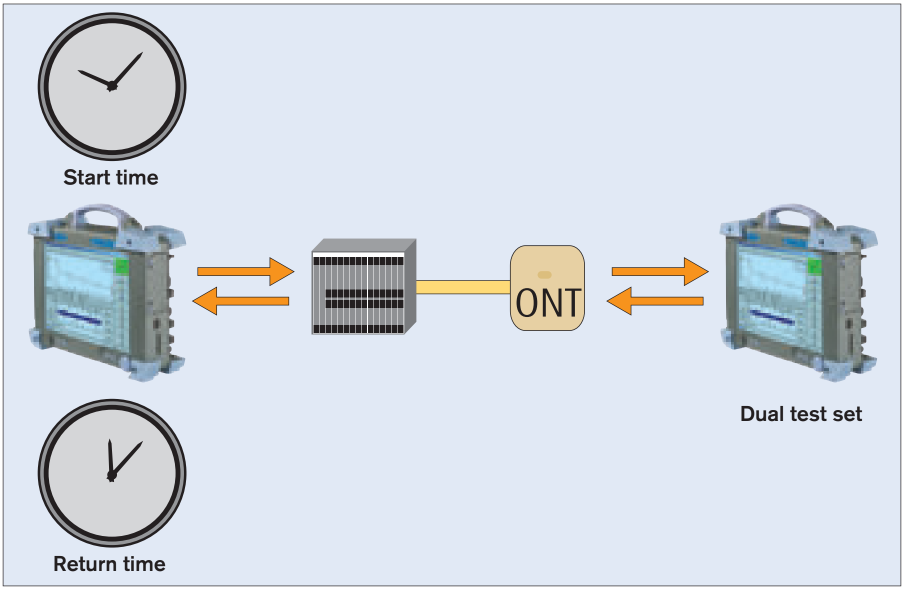


Figure 5.24 – Round-trip latency test

5.2.2.8 BERT over Ethernet

Because EPON is now carried across Layer 1 media, there is a need to certify Ethernet carriage on a bit-per-bit basis. This can be done using BER testing (BERT).

BERT uses a pseudo-random bit stream (PRBS) sequence encapsulated into an Ethernet frame, making it possible to go from a frame-based error measurement to a BER measurement. This provides the bit-per-bit error-count accuracy required for the acceptance testing of physical-medium transport systems.

Short link budget and partial fiber faults will cause a reduced 1 Gigabit Ethernet (GbE) throughput. As a consequence, there is a need to verify the ability for the EPON to fully load the 1 GbE bandwidth without any bit errors.

The test is based on "last-mile" connectivity with the use of physical-layer fiber transceivers, as shown in Figure 5.25.

5.2.2.9 Ethernet Service Acceptance Testing

Ethernet service acceptance testing can be based on an end-to-end test by using two portable instruments and testing from one end to the other. Another way is by sending a technician to one site and test with a device that is mounted onto the network. This type of testing becomes very useful when two technicians cannot be sent at each end at the same time or that the network provider is providing access to the Internet.

All of the tests that are part of the SLA can be performed on either part of the network (end-to-core) or on all of it (end-to-end). The functional diagram of the Ethernet service acceptance testing is shown in Figure 5.26 below.

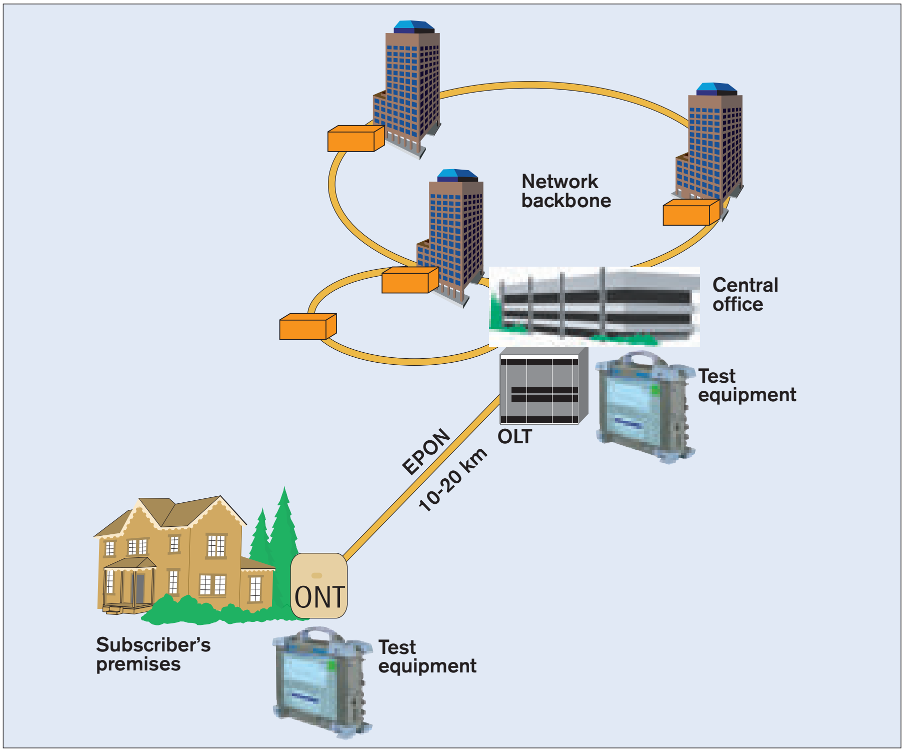


Figure 5.25 – EPON link under test

5.2.2.10 Test Configurations

Different configurations are possible for performing the tests. These are explained below.

Two test sets are required for local/remote testing (see Figure 5.21), also known as head-to-head testing, and formerly as the master/slave configuration. It is ideal for:

- End-to-end testing
- Going through a routed network

In the dual-test-set configuration, the user can have one test set controlling the other by designating one as the "local" test set and the other as the "remote" test set. This makes it easy to determine in which

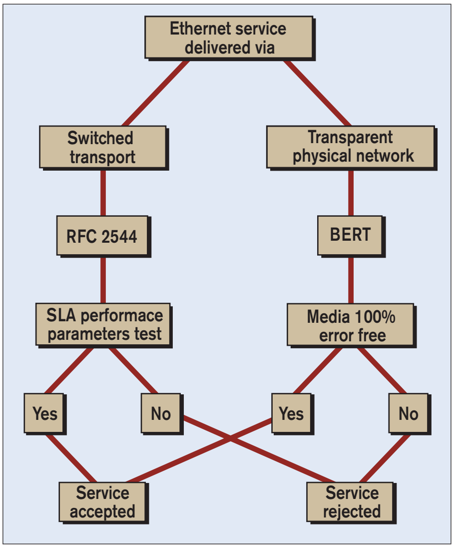


Figure 5.26 – Ethernet service acceptance testing functional diagram

direction the traffic is flowing. Control of the remote test set is assumed via the connection under test. At the end of the test, all of the results are returned to the local test set.

In some cases, testing can be performed using one test set with two ports (see Figure 5.21). This is ideal for:

- Testing a switch locally
- Lab environment
- End-to-end testing with high port density

The single-port loopback configuration is similar to the dual-port configuration in that it requires only one test set. The difference is that the traffic does not go from one port to another but simply loops from the transmit connection of one port into the receive connection of the same port (see Figure 5.21). It is ideal for:

- DWDM systems
- End-to-end testing with end devices that can loop back into the same port, either with a cable or a software loopback.

Note: Many systems (mainly Ethernet switches or routers) will not allow a loop back into the same port. This is due to the fact that switches forward frames according to a destination MAC address. Routers work the same way, but use a destination IP address. If such a device is looped back into the same port it will not know where to forward the frames and will drop them.

5.3 Component Manufacturing

5.3.1 Passive Components

As seen previously, PONs use a number of critical passive components such as:

- Bidirectional 2 x 1 WWDM couplers
- Bidirectional broadband splitters (1 x N)

Figure 5.27 –PON passive component testing during manufacturing

Characterizing these components during manufacturing (see Figure 5.27) is a critical step in ensuring optimum PON performance. Important parameters such as insertion loss, spectral uniformity, bandwidth, isolation (for passive WDM components; called crosstalk for systems) central channel wavelength, polarization dependence, and optical return loss must be controlled and tested during research, development, engineering and production, and sometimes even deployment.

5.3.1.1 Test Methods Based on Broadband Light Sources (BBS)

Loss measurement instruments form what is called a linear system. This means the DUT can be placed anywhere between the source and the detector.

In the optical spectrum analyzer (OSA)-BBS configuration, the DUT is placed directly after the source. The greatest advantage of this setup is the test speed and excellent wavelength resolution and dynamic range capability for a 1xN device, where N is low (such as 1 x 2).

The major drawback of this configuration is that it is a single-channel measurement system. If the DUT is a 1 x 32 splitter, then 32 separate measurements must be taken to complete the DUT testing. In addition, if a polarization-dependent loss (PDL) measurement is required, another test station must be added to the test setup, as PDL cannot be easily measured with an OSA. This has many disadvantages, the most serious being the necessity to connect the same DUT twice (adding unnecessary uncertainty) and then manage an additional batch of test results. Another downside is that at certain wavelengths (especially below 1500 nm), OSAs can become more sensitive to polarization, so testing high-PDL DUTs with an OSA may increase the IL uncertainty by a few tenths of a dB, which can be excessive for most component manufacturers.

5.3.1.2 Test Methods Based on Swept-Delay System

In the swept-delay system, another method that relies on the use of a broadband source, a moving mirror produces interference fringes that are sampled and Fourier-transformed to loss data. In this case, the setup includes a broadband source and usually a Michelson interferometer.

The major advantage of this type of unit is the high optical frequency or wavelength accuracy. A stabilized He-Ne laser is usually used as an optical frequency reference. Until now, the other major advantage of this method was the speed. The optical frequency span over which measurements are possible depends only on the spatial sampling step and ultimately on the broadband source spectrum. The finer this step, the larger the optical frequency span possible. It is thus a question of spatial scanning speed, detection bandwidth and sampling frequency.

The major drawback of this type of apparatus is the reduced optical rejection ratio (equivalent to the signal/source spontaneous emission or S/SSE). If the component is a very narrowband device, then a rejection ratio of 45 dB could be possible (commercially, 35 dB with a 1 nm bandwidth is typically specified by most multiwavelength meters). The other major drawback is the loss uncertainty, which is ± 0.2 dB in the best of cases.

This type of system is not commonly used in production testing of passive components, where loss accuracy and testing efficiency are most critical.

5.3.1.3 Test Methods Based on Swept-Wavelength (or frequency) System

The swept-wavelength (or frequency) method works by sending an optical source signal to the DUT and keeping track of its various reactions, such as fluctuation in power, wavelength or state of polarization (SOP). A detector seizes the responses, used to determine insertion loss (IL), PDL or optical return loss (ORL).

The technique typically uses a tunable laser with constant wavelength adjustment.

A polarization controller is added when PDL measurement is required. Multiple parallel detectors are used, for testing all channels in one scan, thus considerably speeding up the process for multiple-port devices.

The fastest system would use a depolarized scanning source and a detector for each polarization. For a 32-channel device, this means 128 detectors, 32 optical components for polarization splitting, as well as associated electronics. However, this makes for a very complex and expensive solution, a major disadvantage.

5.3.1.4 Compromise Between Testing Time and System Complexity

An intermediate solution between time and complexity is a system using a tunable scanning laser, a polarization controller and low-polarization-dependent response (PDR) detectors. A system capable of performing IL, ORL and PDL measurements on PON passive components is shown in Figure 5.28.

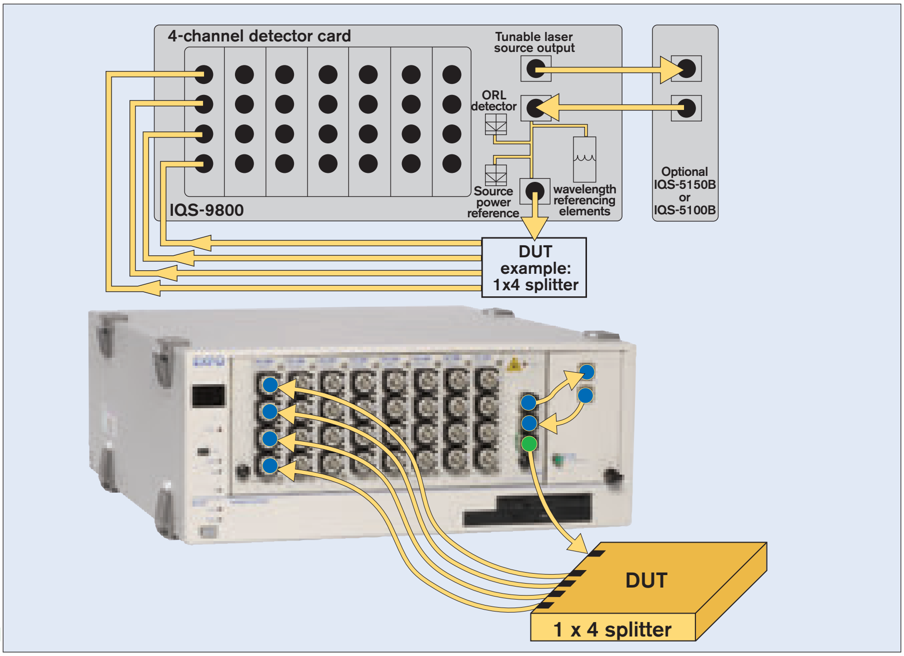


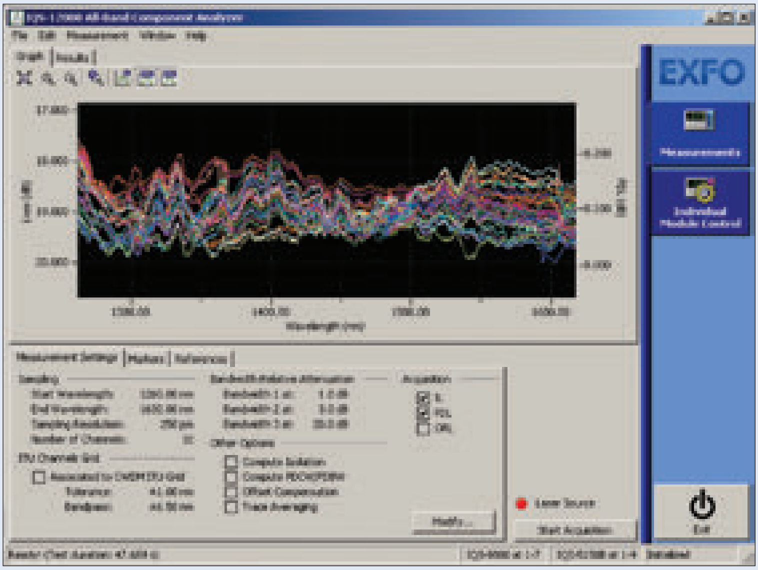
Figure 5.28 –PON test system for PON passive components

The system contains four major components; i.e., the tunable laser, the SOP controller, the reference module and the measurement detectors. These components are optimized for all-band measurements.

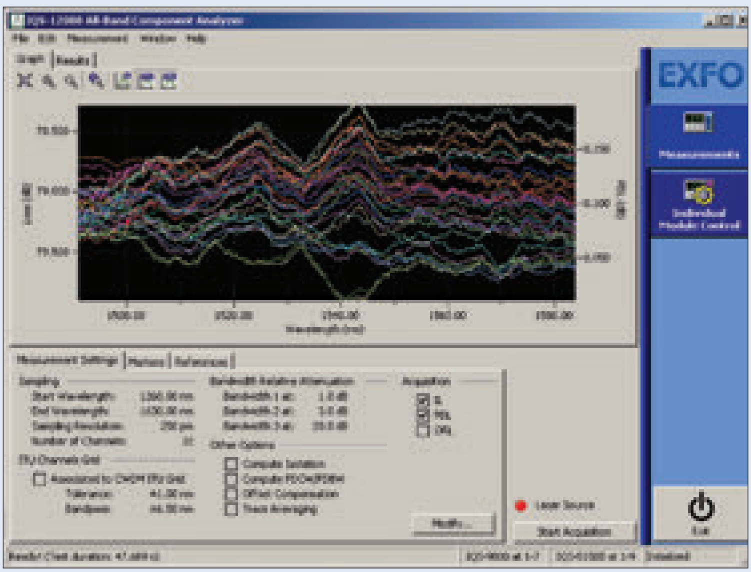
The continuously sweeping all-band tunable laser typically covers the 1260 nm to 1630 nm wavelength range. While the laser is sweeping, the reference module (synchronized with the detectors) provides real-time power and wavelength referencing during the measurement sequence. The SOP controller is made of an adjuster generating the appropriate SOP required for the PDL measurement based on Mueller matrix analysis.

The samples are taken at optical frequency intervals corresponding to at least less than half the laser linewidth. If not, aliasing problems will arise. In a generic swept system, however, the main issue is not the laser linewidth, but rather the total system linewidth. The parameter depends not only on laser linewidth, but also on detector electronic bandwidth and laser scanning speed.

Figure 5.29 provides an example of an IL and PDL test results on a 1 x 32 PON splitter.



(a) Insertion loss and polarization dependent loss of a PON 1 x 32 splitter



(b) Detailed polarization-dependent-loss test results of a PON 1 x 32 splitter

Figure 5.29 – Polarization-dependent-loss test results of a PON 1 x 32 splitter

5.3.1.5 Polarization-Dependent Loss

PDL is the IL due to SOP variation. By definition, PDL is equal to the maximum variation of IL as a function of all possible input SOPs (see Figure 5.30).

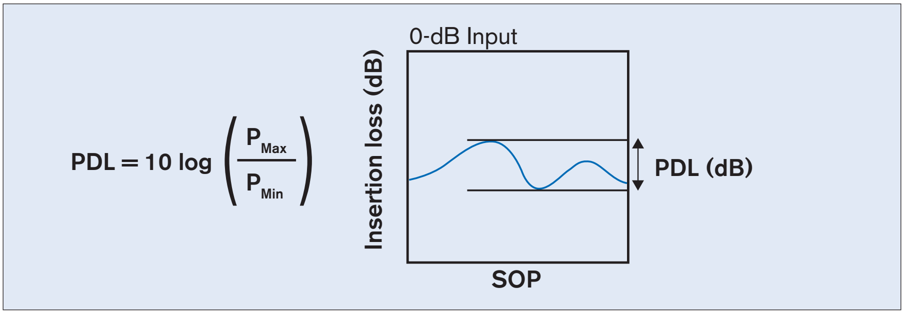


Figure 5.30 – Definition and measurement of polarization-dependent loss

Following the PDL definition the coupling ratio may have a PDL dependency. In that case, the polarization-dependent coupling ratio (PDCR) for each output port 'x' of a coupler/splitter is given in Figure 5.31:

$$\mathbf{PDCR = 10 \log \left(\frac{R_{x,Max}}{R_{x,Min}} \right)}$$

Where for each coupling/splitting port x, the coupling ratio R_x is equal to:

$$\mathbf{R_x = \left(\frac{P_x}{P_{Tot}} \right)}$$

Figure 5 31 – Definition and measurement of polarization-dependent loss

It is important to note that PDL may have wavelength dependence, and angles that reduce reflections may increase PDL. Consequently, component and system manufacturers will always aim for very low PDL. Optical fibers generally have negligible PDL while passive components may have PDL. Series of N PDL elements does not necessarily give the sum of PDL as a whole.

There are three PDL test methods available:

1. Search for the DUT axes (also called all-SOP method), in which the input SOP is varied, typically with Lefebvre polarization controller, to manually search for P_{Max} and P_{Min} The search technique is also called pseudo-random scrambling.
2. Polarization scrambling (all-SOPs), in which the input SOP is randomly varied, typically with an electronic polarization controller. Different techniques are available for polarization control: motorized Lefebvre, waveplates, squeezed fiber, liquid crystal, etc.
3. Mueller matrix (also called fixed-SOP Mueller matrix), in which four input

SOPs (horizontal, vertical, 45° and right-hand circular) are used to reconstruct the 4 x 4 Mueller matrix (with the source wavelength being scanned for each SOP). The procedure is illustrated in Figure 5.32.

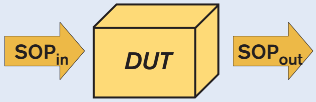
The Mueller matrix approach is typically the mostly used because it can be easily automated and testing is fast. Its drawback is related to its high cost.

5.3.2 Active Components

The most critical parameters to be considered in production testing are:

- Central wavelength
- Bandwidth (spectral distribution and linewidth)
- Frequency stability/temperature control (when applicable)
- Output power stability/control
- Life time (failure in time - FIT).

Figure 5.32 illustrates an example of long-term source power and frequency stability. The test is performed by a multiwavelength meter because of its much better wavelength resolution (resolution bandwidth) than the one provided by an OSA. However, an OSA will be used to measure the power spectrum of a source such as laser as a function of wavelength as shown in Figure 5.33.



$$SOP_{out} = (M)\, SOP_{in}$$

SOP_{in}	Power output No device	Power output With device
Horizontal 0°	P_a	P_1
Vertical 90°	P_b	P_2
Diagonal 45°	P_c	P_3
Circular Right	P_d	P_4

$$T_1 = P_1/P_a$$

$$T_2 = P_2/P_b$$

$$T_3 = P_3/P_c$$

$$T_4 = P_4/P_d$$

$$\begin{pmatrix} m_{11} \\ m_{12} \\ m_{13} \\ m_{14} \end{pmatrix} = \begin{pmatrix} (T_1 + T_2)/2 \\ (T_1 - T_2)/2 \\ T_1 - m_{11} \\ T_4 - m_{11} \end{pmatrix}$$

$$T_{max} = m_{11} + \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}$$

$$T_{min} = m_{11} - \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}$$

$$PDL_{dB} = -10\log\left(\frac{T_{max}}{T_{min}}\right)$$

Figure 5.32 – PDL test procedure based on Mueller matrix

It is to be noted that an OSA does not provide the exact power spectral distribution of a DFB because a DFB without coherence control can have a linewidth of the order of 100 kHz full width at half the maximum (FWHM), while a DFB with coherence control will have a linewidth in the MHz range, both too narrow to be perfectly resolved by an OSA. Consequently the OSA simply provides its own filter spectral shape as a result. The resolution bandwidth of an OSA is a critical parameter because it indicates how spectrally narrow the OSA filtering is at -3 dB or FWHM. However, the resolution bandwidth at much less power such as at -20 dB will tell how uniformly smooth (without any artifact) and still narrow enough for the OSA filter to resolve sufficiently down in power range. It is not surprising to find laboratory OSAs with the narrowest resolution bandwidth on the market; the pertinent question to ask is how narrow or how wide or how many artifacts the filtering shape of this OSA would offer: this is a value to look for to determine the quality of an OSA.

To fully resolve a very narrow power spectral distribution, a wavemeter (also called an interferometer) must be used. This instrument is best to resolve narrow line shape but, unfortunately, cannot provide the power amplitude values: perfection does not exist; what you win on one side, you lose on the other side and you must accept compromises.

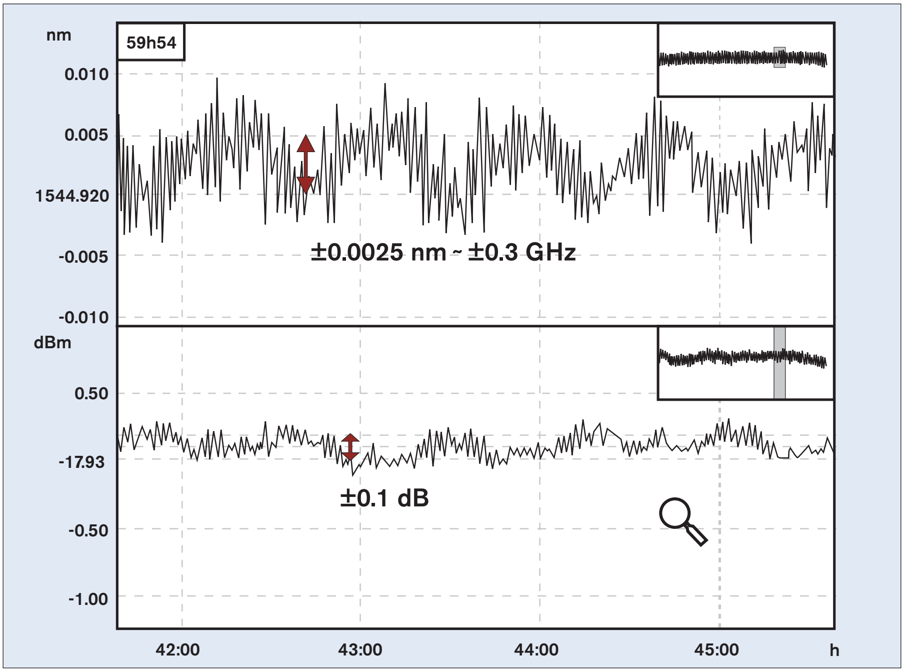


Figure 5.33 – Example of long-term optical source power and frequency stability

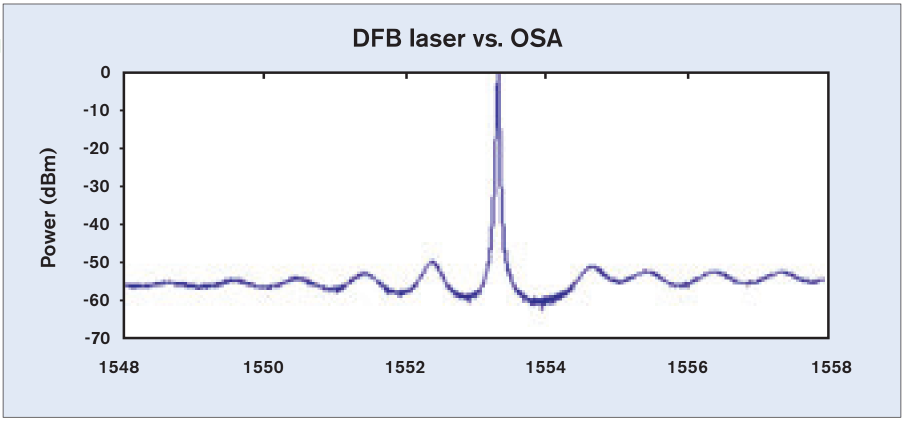


Figure 5.34 – Example of DFB laser spectral power distribution with an OSA

Chapter 6

Conclusion

Conclusion

Since the mid 90s, the FTTH PON market has been developing mainly in Asia, even though it started from the initiative of network operators in North America and Europe as well as in Asia. Since early 2002, however, there has been a tremendous business attraction to this technology, mostly in the US, due to a consortium of operators including Verizon, SBC and Bellsouth. With the early and strong commitment of Verizon and SBC, it is foreseen that the market will shortly boom to millions of subscribers in the US.

The technology will continue to evolve rapidly. For instance, digital video will be used more and more instead of analog video overlay, bringing many advantages to the physical layer:

- No EDFA required at the CO
- Much lower optical power requirements than analog, eliminating NLE and reducing safety issues
- Better power budget/more cost effectiveness
- Fewer problems related to reflection, allowing the use of UPC connectors instead of expensive APCs
- Easier installation and maintenance
- Overall lower cost

The use of video over IP offers the following additional benefits:

- No separate wavelength required for video
- Upstream video transmission possible
- More business potential
- Extremely robust encryption techniques required (as well as for digital).

Another change that may come is placing the ONT inside the subscriber's premises, rather than outside. This would result in:

- Much less stringent environmental requirements (Category C – controlled, instead of E - extreme)
- The ONT can be used inside the setup box (STB)
- The battery backup can be incorporated inside the STB with remote monitoring, removing the burden of responsibility from the subscriber
- Tremendously lower cost
- Another network demarcation point is required

Current PON designs have brought many challenges at the product and testing levels and future developments will continue to do the same. The present book has discussed these aspects as well as the essential development of international standards. The ITU-T and IEEE have shown the way with the development of standards documents mainly geared toward the network level. The IEC and other regional organizations such as the TIA have started to do the same, this time in the area of product specifications and performance, interface and reliability standards, together with test methods and test procedures. Mature, universally accepted standards are the backbone of this exciting technology.

The three proposed PON architectures (BPON, GPON and EPON) offer various advantages but also some drawbacks, like any other technology. But most of all, they are considered under various assumptions, hypotheses, market applications. The following table offers an overall summary of the major differences between BPON, GPON and EPON for P2MP topology.

	BPON	GPON	EPON	Others/future
Motivation	Beginner Low cost	Flexible There for a long time	Widespread low cost technology	Better splitter loss issue
Major advantage	ATM	Any traffic Highest BW	Low cost Internet application	Unlimited BW WDM
Major drawback	Soon BW limited	Splitting loss limited	Fixed BW limited	High cost muxing
	Never developed for video			
Application	Small community	All	Apartment building	CWDM in access: overall lower cost
Future Long term	Limited	Needs new splitting technology	10Gb EPON	CWDM (muxing instead of splitting)

Finally, PON is seen as the best long term solution for the public telephone telegraph (PTT) companies to compete head-to-head against the CATV service providers. But we believe that the following conditions must be met in order to set the proper environment for succesful PON deployment.

1. No telecommunication market restriction / market totally opened to competition
2. Heavily challenged telephone companies: no single dominant telephone company
3. Favorable government FTTH policy / regulations
4. Population aware of, consuming, desiring telecommunications technologies
5. Optical fiber used as a marketing incentive by home builders
6. Favorable economic and social conditions for population to consume TV and especially HDTV

Many think that these conditions will finally be met over time for the benefit of people all over the world, similar to what happened with Internet not so long ago. Only time will tell.

CONCLUSION

Chapter 7

Glossary

GLOSSARY

A

Address Resolution Protocol (ARP): A network-layer protocol used in TCP/IP transmission. ARP is used by end stations to determine the physical address of other stations on the same LAN.

Asynchronous: Said of transmission in which sending and receiving devices are not synchronized. Data division is indicated by data itself, which carries these signals.

Asynchronous Transfer Mode (ATM): A data networking protocol used for high-bandwidth, low-delay, connection-oriented, packet-like switching and multiplexing.

ATM adaptation layer type 0 (AAL0): Refers to raw ATM cells

ATM adaptation layer type 1 (AAL1): Supports constant bit rate, time dependent traffic such as voice and video

ATM adaptation layer type 2 (AAL2): Reserved for variable bit rate video transfer

ATM adaptation layer type 3/4 (AAL3/4): Supports variable bit rate, delay tolerant data traffic requiring some sequencing and/or error detection support

ATM adaptation layer type 5 (AAL5): Supports variable bit rate, delay tolerant connection oriented data traffic requiring minimal sequencing or error detection support

Auto-Negotiation (AN): Algorithm that allows two devices at either end of a single link segment or of multiple link segments, separated by media conversion, to negotiate a common data service function

B

Backbone: Part of the network that joins several local-area networks, either inside a building or across a city or country. This is achieved through a cable connection between telecommunication or wiring closets, floor distribution terminals or entrance facilities. In star networks, the backbone cable interconnects hubs and similar devices, as opposed to cables running between hub and station. The backbone is the part of the communications network that carries the heaviest traffic.

Backoff Delay: In Ethernet transmission, the backoff delay is the length of time that a station waits before retransmitting a frame, after a data collision is detected. This operation applies to carrier-sense multiple-access networks with collision detect (CSMA/CD; see separate entry).

Baseband: A transmission method in which one single digital signal uses an entire bandwidth. The unmodulated signal is sent directly over the transmission medium. Baseband is simpler, cheaper and less sophisticated than broadband. All Ethernet media types are baseband except for 10Broad36, which is broadband.

Bandwidth: The range of frequencies required for proper transmission of a signal. Bandwidth represents the amount of data that can be transmitted through a communications channel in a fixed amount of time. For digital devices, it is usually expressed in bits (or bytes) per second, whereas for analog devices, it is expressed in cycles per second, or in hertz (Hz). The greater the bandwidth, the greater the information-carrying capacity and the faster the speed. A continuous frequency range starting from zero is said to be baseband, while a range starting substantially above zero is considered broadband.

Bit: Basic unit for digital telecommunication transport signal (bit 1 means transmitter signal is on – bit 0 means transmitter signal is off – also basic binary (based on 2) unit characterizing the number of levels used to digitalize an analog signal (for instance an 8-bit digital signal means that its corresponding analog signal has been divided into 256 (2^8) different discrete levels in order to digitalize it). Always used in the singular form when specifying data rates (e.g. 155.52 Mb/s).

Bit Error Rate (BER): A measure of data integrity referring to the number of digital highs that are interpreted as lows (and vice versa), divided by the total number of bits received. The BER ratio is often expressed as a negative power of ten.

Bridge: Specified in IEEE 802.1D standard, a bridge is a device that connects two or more networks at the data-link layer (Layer 2). Bridges are not part of the collision domain; i.e., they may be used to split a network into multiple collision domains.

Broadband: A transmission medium whose bandwidth capacity is sufficient to carry multiple voice, video or data channels simultaneously. Each channel is modulated to a different frequency bandwidth and occupies a different place on the transmission medium; the signals are then demodulated to their original frequency at the receiving end.

Broadcast: The act of sending a frame to all network stations. Also describes the class of media (designed especially for CSMA/CD Ethernet) in which all stations are capable of receiving a signal transmitted by any other station.

Broadcast Address: A multicast address that identifies all the stations on a network.

Broadcast Domain: A restricted area that allows all connected devices to transmit and receive information from each other. The devices are interconnected through bridges, allowing them to share the transmission medium and, consequently, the data.

Byte: A group of 8 bits. Also known as an octet.

C

Carrier Sense: A method of detecting the presence of signal activity on a common channel. With Ethernet, a method of detecting whether another station is transmitting.

Carrier-Sense Multiple-Access with Collision Detection (CSMA/CD): A network access method used by Ethernet in which a station listens for traffic before transmitting. If two stations transmit simultaneously, a collision is detected and both stations wait a brief time before attempting to transmit again. So called because it a) allows multiple stations to access the broadcast channel at will, b) avoids contention via carrier sense and deference, and c) resolves contention via collision detection and retransmission.

Channel: A logical medium in a communication system over which data is transmitted.

Chromatic Dispersion (CD): Phenomenon caused by the wavelength dependence of the index of refraction in an optical fiber. Since any practical light source has a finite spectral width, CD results in pulse broadening.

Coarse Wavelength-Division Multiplexing (CWDM): Method of combining multiple signals on laser beams at various wavelengths for transmission along fiber-optic cables. The wavelength spacing is set between 1000 GHz and 50 nm. It is also characterized by non-thermally cooled laser transmitters.

Collision: A simultaneous meeting of two or more data signals from different channels.

Collision Detect (CD): A method to detects two or more simultaneous transmissions on a common signal channel.

Contention: Interference between colliding transmissions (see collisions).

Cyclic Redundancy Check (CRC): Error-checking technique used to ensure the accuracy digital-code transmission over a communications channel. The transmitted signals are divided into predetermined lengths which, used as dividends, are divided by a fixed divisor. The remainder of the calculation is appended onto and sent with the message. At the receiving end, the computer recalculates the remainder. If it does not match the transmitted remainder, an error is detected.

D

Data-Link Layer: Layer 2 of the OSI reference model. This layer takes data from the network layer and passes it on to the physical layer (layer 1). The data-link layer is responsible for transmission and reception of Ethernet frames, 48-bit addressing, etc. It includes both the media access control (MAC) and logical link control (LLC) layers.

Dense Wavelength-Division Multiplexing (DWDM): A technology that enables a single optical fiber to carry multiple frequency channels (or wavelengths). Channel spacing is set at ≤ 1000 GHz.

Destination MAC Address: Address identifying the station or stations on a LAN to which a frame is being sent.

DSL access multiplexer (DSLAM): An xDSL line-interface device located in the CO, one side connected to premise UNIs over local loop, and the other side connected to PSTN Frame Relay or ATM-based network system

Duplex: Circuit used to transmit signals simultaneously in both directions.

E

Electronic Industry Association (EIA): An association of manufacturers and users that establishes standards and publishes test methodologies. Formerly known as RMA or RETMA.

Excessive Collision Error: Error that causes frame loss. This type of error occurs when a station receives 16 consecutive collisions while attempting to transmit a single frame; then the frame is dropped due to the excessive collisions.

F

Fast Ethernet: Ethernet standard supporting 100 Mb/s operation.

Fiber-to-the-x (FTTx): The x in fiber-to-the-x is a variable indicating the point at which the fiber in a network stops and copper (coaxial or twisted-pair) cabling takes over; e.g., fiber-to-the-home (FTTH), fiber-to-the-building (FTTB), fiber-to-the-premises (FTTP), fiber-to-the-cabinet (FTTCab), fiber-to-the-curb (FTTC), etc. The further the fiber goes, the wider the bandwidth, the quicker the speed, and the more applications and services can be offered.

Flow Control: The process of controlling data transmission at the sender to avoid overfilling buffers and loss of data at the receiver.

Frame: The sequence of bits that form the unit of data transmission at the data-link layer. In Ethernet, a frame consists of the sequence of bits transmitted by a station from the preamble through the frame check sequence. Also known as a packet.

Frame Check Sequence (FCS): An encoded value appended to each frame by a transmitting station to allow transmission errors to be detected by the receiving station. Implemented as a 32-bit cyclic redundancy check (CRC) code.

Full-Duplex: Data transmission over a circuit capable of transmitting in both directions simultaneously.

G

Gb/s, Gbit/s or Gbps: Gigabit per second. One Gb/s equals one billion bits per second.

Generic Framing Procedure (GFP): Traffic adaptation protocol providing convergence between packet-switched and transmission networks. GFP elegantly maps packet-based protocols such as Ethernet, Fibre Channel, FICON, ESCON, and various forms of digital video into SONET/SDH, typically using virtual concatenation to provide right-sized pipes for data services. Used in GPON.

Gigabit Ethernet (GigE or GbE): A version of Ethernet that operates at 1 Gb/s (nominal 1000 Mb/s).

H

Half-Duplex: Data transmission over a circuit capable of transmitting in either direction, but not simultaneously.

Headend: The equipment in a cable system which receives the various program source signals, processes them, and retransmits them to subscribers.

High-definition television (HDTV): A TV signal with higher resolution and higher fidelity than the conventional TV. In North America, NTSC TV format is used. PAL is used in Europe. HDTV picture has twice as much resolution than NTSC format.

Hub: A device at the center of a star topology network. Hubs can be active (where they repeat signals set to them) or passive (where they do not repeat but merely split signals sent through them). Hub may refer to a repeater, bridge, switch, router, or any combination of these.

Hybrid fiber coax (HFC): Broadband bidirectional shared media transmission system using optical fiber between the CO and fiber nodes and coaxial distribution from the fiber nodes and subscriber's premises

I

IEEE: Institute of Electrical and Electronics Engineers. A professional organization and standards body. The IEEE Project 802 is the group within IEEE responsible for LAN technology standards.

IEEE 802.1: The IEEE standards committee defining high-level interfaces, network management, internetworking, and other issues common across LAN technologies.

IEEE 802.2: The IEEE standards committee defining logical link control (LLC).

IEEE 802.3: The IEEE standards committee defining Ethernet networks.

IEEE 802.3ah: 2004 standards where EPON is specified.

Integrated services digital network (ISDN): An all-digital communications line that allows for the transmission of voice, data, video and graphics, at very high speeds, over standard communication lines.

Inter-Frame Gap (IFG): The delay or time gap between frames. Also called inter-packet gap.

Internet Protocol (IP): Method or protocol by which data is sent from one computer to another on the Internet. Each computer on the Internet has at least one IP address that uniquely identifies it from all other computers on the Internet. Because of these standardized IP addresses, the gateway receiving the data can keep track of, recognize and route messages appropriately.

Inter-Packet Gap (IPG): The delay or time gap between packets. Also called inter-frame gap.

J

Jitter: The slight movement of a transmission signal in time or phase that can introduce errors and loss of synchronization. More jitter will be encountered with longer cables, cables with higher attenuation, and signals at higher data rates. Also, called phase jitter, timing distortion, or intersymbol interference.

K

Kb/s, Kbit/s or Kbps: Kilobit per second. One Kb/s equals one thousand bits per second.

L

Link: A transmission path between two points. The link does not include any of the terminal equipment, work-area cables, or equipment cables.

Local-Area Network (LAN): A term used to refer to a form of networking technology that implements a high-speed, relatively short distance form of computer communications. Ethernet is one type of LAN.

M

MAC Address: The 48-bit address used in Ethernet to identify a station. Generally a unique number that is programmed into a device at time of manufacture.

MAC Frame: Name for the data unit exchanged between peer Medium Access Control sublayer entities. Also called simply a "frame".

Mb/s, Mbit/s or Mbps: Megabits per second. One Mb/s equals one million bits per second.

Media: Wire, cable, or conductors used for transmission of signals.

Medium Access Control (MAC): A mechanism operating at the data link layer of local-area networks which manages access to the communications channel (medium). It forms the lower layer of the IEEE data link layer (OSI layer 2) which complements the Logical Link Control (LLC). MAC is a media-specific protocol within the IEEE 802 specifications.

Medium-Dependent Interface (MDI): The connector used to make the mechanical and electrical interface between a transceiver and a media segment. An 8-pin RJ-45 connector is the MDI for the 10Base-T, 100Base-TX, 100Base-T2, 100Base-T4, and 1000Base-T media systems.

Media-Independent Interface (MII): Used with 100 Mb/s Ethernet systems to attach MAC level hardware to a variety of physical media systems. An MII provides a 40-pin connection to outboard transceivers (also called PHY devices).

Metropolitan-Area Network (MAN): A network, often ringed in structure, that covers an entire city and its suburbs. Also known as a metro network.

Multicast: An addressing mode in which a given frame is targeted to a group of logically related stations.

Multicast Address: An address specifying a group of logically related stations on a network. Also called a group address.

Multiprotocol label switching (MPLS): set of procedures for augmenting network layer packets with label stacks, thereby turning them into labeled packets.

N

Node: End point of a network connection. Nodes include any device connected to a network such as file servers, printers, or workstations.

O

Octet: Eight bits (also called "byte")

Optical Time-Domain Reflectometry/Reflectometer (OTDR): A method or instrument for evaluating optical fiber based on detecting and measuring backscattered (reflected) light. Used to measure fiber length and attenuation, evaluate splice and connector joints, locate faults, and certify cabling systems.

Open Systems Interconnection (OSI): A communications reference model developed by the International Standards Organization (ISO). This model defines seven layers, each of which provides a subset of all of the LAN services. This layered approach allows small groups of related services to be implemented in a modular fashion that makes designing network software much more flexible.

P

Packet: Bits grouped serially in a defined format, containing a command or data message sent over a network. Same as a frame.

Passive Optical Network (PON): Network in which fiber-optic cabling (instead of copper) brings signals all or most of the way to the end-user. It is described as passive because no active equipment (electrically powered) is required between the central office (or hub) and the customer premises. Depending on where the PON terminates, the system can be described as an FTTx network, which typically allows a point-to-point or point-to-multipoint connection from the central office to the subscriber's premises; in a point-to-multipoint architecture, a number of subscribers (for example, up to 32) can be connected to just one of the various feeder fibers located in a fiber distribution hub, dramatically reducing network installation, management and maintenance costs. Three types of PON are BPON, GPON, EPON.

Physical Address: The unique address value associated with a given station on the network. An Ethernet physical address is defined to be distinct from all other physical addresses on the network.

Physical Layer: Layer one of the seven-layer ISO Reference Model for Open Systems Interconnection. This layer is responsible for the transmission of signals – electrical, optical, or radio – between computing machines.

Physical-medium attachment sublayer (PMA): The part of the physical layer between the Attachment Unit Interface (AUI) and Medium Dependent Interface (MDI) in 10 Mb/s Ethernet PHYs, and between the PCS and PMD in 100 Mb/s fast Ethernet PHYs, as defined in IEEE Std. 802.3-1998

Physical-medium-dependent sublayer (PMD): The part of the 100 Mb/s fast Ethernet PHYs between the PMA and the media conversion sublayer

Polarization Mode Dispersion: Delay between the two principal states of the light polarization propagating along a fiber or through a device due to the birefringence property of the material. PMD causes pulse broadening.

Preamble: A sequence of 62 encoded bits transmitted (by a station) before each frame to allow for the synchronization of clocks and other physical-layer circuitry at other stations on the channel.

Propagation Delay: The signal transit time through a cable, network segment, or device.

Protocol: A formal set of rules governing the format, timing, sequencing and error control of data exchange across a network. Many protocols may be required and used on a single network.

R

Registered Jack (RJ): A term from the telephone industry, used for jacks (connectors) that were registered for use with particular types of telephone services.

Repeater: A device that receives, amplifies (and sometimes reshapes), and retransmits a signal. It is used to boost signal levels and extend the distance a signal can be transmitted.

RJ-45: A USOC code identifying an 8-pin modular plug or jack used with unshielded twisted pair cable. Officially, an RJ-45 connector is a telephone connector designed for voice grade circuits only. RJ-45 type connectors with better signal handling characteristics are called 8-pin connectors in most standards documents, though most people continue to use the RJ-45 name for all 8-pin connectors.

Routers: These are more complex internetworking devices that are also typically more expensive than bridges. They use Network Layer Protocol Information within each packet to route it from one LAN to another.

S

Simplex Transmission: Data transmission over a circuit capable of transmitting in one preassigned direction only.

Slot Time, timeslot or timestamp: A key parameter for Ethernet network operation. Defined as 512 bit times for Ethernet networks operating below 1 Gb/s, and 4096 bit times for Gigabit Ethernet. In order for each transmitter to reliably detect collisions, the minimum transmission time for a complete frame must be at least one slot time, whereas the round-trip propagation delay (including both logic delays in all electronic components and the propagation delay in all segments) must be less than a slot time.

SNMP: Simple Network Management Protocol

Star Topology: A network configuration in which there is a central point to which a group of systems are directly connected. All transmissions from one system to another pass through this central point.

Station: A unique, addressable device on a network. A station is identified by a destination address (DA).

Station Address: see MAC Address

STP: Shielded Twisted Pair

Synchronous: Transmission in which the data character and bits are transmitted at a fixed rate with the transmitter and receiver being synchronized.

Synchronous Digital Hierarchy (SDH): Standardized by the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T). A protocol for transmitting information over optical fiber.

Synchronous Optical NETwork (SONET): Standardized by the American National Standards Institute (ANSI). A protocol for backbone networks, capable of transmitting at extremely high speeds and accommodating gigabit-level bandwidth.

T

Time-Domain Reflectometry (TDR): A technique for measuring cable lengths by timing the period between a test pulse and the reflection of the pulse from an impedance discontinuity on the cable. The returned waveform reveals many undesired cable conditions, including shorts, opens, and transmission anomalies due to excessive bends or crushing. The length to any anomaly, including the unterminated cable end, may be computed from the relative time of the wave return and nominal velocity of propagation of the pulse through the cable. See also Optical Time-Domain Reflectometry.

Transmission Control Protocol (TCP): Provides a reliable stream delivery and virtual connection service to applications through the use of sequenced acknowledgement with retransmission of packets when necessary (TCP/IP).

U

Unshielded Twisted Pair (UTP): Twisted pair cabling that includes no shielding. UTP most often refers to the 100 Ω Category 3, 4, and 5 cables specified in the TIA/EIA 568-A standard.

V

Virtual channel identifier (VCI): Represents the routing information within the ATM cell.

Virtual Concatenation (VCAT): Process enabling transport pipes to be "right-sized" for various data payloads by allowing SONET/SDH channels to be multiplexed in arbitrary arrangements. VCAT breaks down data packets and maps them into the base units of TDM frames. This data is then grouped in multiple data flows of varying size to create larger, aggregate payloads optimally sized to match available SONET/SDH pipe capacity. VCAT is applied at the end-points of the connections, which permits each channel used to be independently transmitted through a legacy transport network.

Virtual LAN: A method in which a port or set of ports in a bridge or switch are grouped together and function as a single "virtual" LAN.

Virtual path identifier (VPI): Together, VCI and VPI make up the VPCI and represent the routing information within the ATM cell.

Virtual Private Network (VPN): One or more wide-area network links over a shared public network, typically over the Internet or an IP backbone from a network service provider (NSP), that simulates the behavior of dedicated WAN links over leased lines.

Voice-over-Internet-Protocol (VoIP): Refers to communications services–voice, facsimile and/or voice-messaging applications–that are transported via the Internet,rather than the public switched telephone network. In an Internet-based telephone call, the voice signals are converted to digital format and compressed/translated intoInternet protocol (IP) packets for transmission over the Internet; the process is reversed at the receiving end.

W

Wavelength-Division Multiplexing (WDM): Optical transmission technique that uses different light wavelengths to send data. Combination of two or more optical signals for transmission over a common optical path.

Wide-Area Network (WAN): A network that links data processing and telecom equipment over a larger area than a single work site or metropolitan area. A WAN usually links cities and is based on X.25 packet switching.

Wide Wavelength-Division Multiplexing (WWDM): A technology that enables a single optical fiber to carry multiple wavelength bands. Channel spacing is set at ≥ 50 nm.

0-9

10 GigE or 10 GbE: 10 Gigabit Ethernet

4B/5B Code: Scheme used to encode data for transmission in which 4-bit binary data values are encoded into 5-bit symbols for transmission across the network media. 4B/5B is used with Ethernet 100Base-TX and 100-Base-FX media systems.

8B6T: Signal encoding method used with the 100Base-T4 Ethernet media system.

8B/10B Code: Scheme used to encode data for transmission in which 8-bit binary data values are encoded into 10-bit symbols for transmission across the network media. 8B/10B is used with 1000Base-X Gigabit Ethernet media systems and 10G Base-LX4.

Chapter 8

Abbreviations and Acronyms

Abbreviations and Acronyms

A

AAL	ATM adaptation layer
AAL0	ATM adaptation layer type 0 – refers to raw ATM cells
AAL1	ATM adaptation layer type 1 – supports constant bit rate, time dependent traffic such as voice and video
AAL2	ATM adaptation layer type 2 – reserved for variable bit rate video transfer
AAL3/4	ATM adaptation layer type 3/4 – supports variable bit rate, delay tolerant data traffic requiring some sequencing and/or error detection support
AAL5	ATM adaptation layer type 5 – supports variable bit rate, delay tolerant connection oriented data traffic requiring minimal sequencing or error detection support
ABR	Available bit rate
ADM	Add/drop multiplexer (or multiplexing)
ADS	Additional digital service
ADSL	Asymmetric digital subscriber line
AI	Adapted information
AN	Auto-negotiation – algorithm that allows two devices at either end of a single link segment or of multiple link segments, separated by media conversion, to negotiate a common data service functionANSIAmerican National Standards Institute (www.ansi.org)
AP	Access point
APC	Angled physical contact/angled polished connector
APD	Avalanche photodiode – type of optical detector
APON	ATM-based passive optical network
ATM	Asynchronous transfer mode (www.atmforum.com)
AWG	Array waveguide grating

B

b	Bit
B	Byte (= 8 bits)
BAsize	Buffer allocation size – size (in bytes) that the receiver has to allocate to capture all the data
BCH	Bose-Chaudury-Hockenheim – FEC coding
BDG	Bulk diffraction grating
BER	Bit error rate (ITU-T uses bit error ratio)
BERT	BER testing
BIP	Bit-interleaved parity
B-ISDN	Broadband integrated-service digital network
BLEC	Building local-exchange carrier
BOG	Bulk optic grating
BPON	Broadband passive optical network
Btag	Beginning tag

C

CATV	Cable television
CBR	Constant bit rate
CD	Chromatic dispersion Collision detection (Ethernet)
CDV	Cell delay variation
CER	Cell error ratio
CI	Characteristic information
CID	Channel identification
CIR	Committed information rate
CLEC	Competitive local-exchange carrier
CLP	Cell loss priority
CL-PS	Connectionless packet service
CLR	Cell loss ratio
CMR	Cell miss-sequence/insertion
CNR	Carrier-to-noise ratio
CO	Central office
COCS	Connection-oriented circuit service
CONS	Connection-oriented network service
COPS	Connection-oriented packet service
CoS	Class of service
COTS	Connection-oriented transport service
CPCS	Common part convergence sublayer
CPE	Customer premises equipment
CPI	Channel path identifier
CPS	Common-part sublayer
CRC	Cyclic redundancy check (calculated over the SAR header)
CS	Convergence sublayer (ATM) Carrier sense (Ethernet)
CSI	Convergence sublayer indicator – used for residual time stamp for clocking
CSMA	Carrier-sense media access
CSMA/CD	Carrier-sense multiple access with collision detection
CSO	Composite second-order beat noise (analog transmissions)
CTB	Composite triple-beat noise (analog transmissions)
CTD	Cell transfer delay
CWDM	Coarse wavelength-division multiplexing

D

DBA	Dynamic bandwidth assignment/allocation
DBR	Dynamic bandwidth report (upstream)
DBS	Direct broadcast service
DFB	Distributed-feedback (laser)
DGD	Differential group delay
DiffServ	Differentiated services
DSL	Digital subscriber line
DSLAM	DSL access multiplexer – an xDSL line-interface device located in the CO, one side connected to premise UNIs over local loop, and the other side connected to PSTN Frame Relay or ATM-based network system
DUT	Device under test
DWDM	Dense wavelength-division multiplexing
DWS	Dynamic wave slicing

E

EDFA	Erbium-doped fiber amplifier
EFM	Ethernet in the first mile (www.ethernetinthefirstmile.com)
EFMA	Ethernet in the first mile alliance (www.efmalliance.org)
EIA	Ethernet Internet access Electronic Industry Association (part of the Telecommunications Industry Association)
EIR	Excess information rate
EPC	Even-parity check calculated over the CRC
EPD	Early packet discard
EPON	Ethernet-based passive optical network
ESR	Ethernet service rate
Etag	End tag – similar to Btag
ETC_CI	Ethernet coding characteristic information
ETH	Ethernet media–access-control layer network
ETH_CI	Ethernet media-access-control characteristic Information
Ethernet	LAN protocol synonymous with developed under IEEE 802.3 standard
ETYLR	Ethernet physical-link rate
ETYn	Ethernet physical-layer (PHY) network of order n
ETYR	Ethernet physical interface rate

F

FBG	Fiber Bragg grating
FBT	Fused biconic tapered (fiber)

FC	Fiber connector
FCC	Federal Communications Commission (USA) (www.fcc.gov)
FCS	Frame check sequence
FD	Flow domain
FDDI	Fiber distributed data interface, standardized by ANSI
FDF	Flow domain flow
FDH	Fiber distribution hub
FEC	Forward error correction
FEFI	Far-end fault indication
FFS	For further study
FFU	For future use
FP	Flow point Fabry-Perot (laser)
FPP	Flow point pool
FR-SSCS	Frame relay service specific convergence sublayer
FSAN	Full-Service Access Network (forum) (www.fsanweb.org)
FT	Flow termination
FTP	File transfer protocol (TCP/IP)
FTTC	Fiber-to-the-curb
FTTH	Fiber-to-the-home
FTTP	Fiber-to-the-premises
FUT	Fiber under test
G	
GbE	Gigabit Ethernet
Gbit	Gigabit (1 000 000 000 bits)
GEM	GPON encapsulation method
GFC	Generic flow control
GFP	Generic framing procedure
GPON	Gigabit-capable passive optical network
GR	General requirement (document from Telcordia)
H	
HDD	Horizontal direct drilling
HDSL	High-bit-rate digital subscriber line
HDTV	High-definition television
HEC	Header error control (ATM)
HFC	Hybrid fiber coax
HTTP	Hypertext transfer protocol (TCP/IP)

I	
IAD	Integrated access device
IAD	Integrated access device
IEC	International Electrotechnical Commission (www.iec.ch)
IEEE	Institute of Electrical and Electronic Engineers (www.ieee.org)
IETF	Internet Engineering Task Force (www.ietf.org)
IL	Insertion loss
ILEC	Incumbent local-exchange carrier
IP	Internet protocol
IPTV	Internet protocol TV (www.internetprotocoltelevision.com)
ISDN	Integrated services digital network
ISO	International Standards Organization (official name is now: Organization for international standardization - ISO)
ITU	International Telecommunication Union (www.itu.int)
ITU-T	ITU - Telecommunications standardization sector
J	
JPEG	Joint photographic experts group
K	
kb or kbit	kilobit (1 000 bits)
L	
LAN	Local-area network
LCAS	Link capacity adjustment scheme
LEC	Local-exchange carrier
LF	Link flow
LFD	Live fiber detector
LI	Length indication – contains the length of the SAR SDU in bytes
LLC	Logical link control
LLID	Logical link identification
LSB	Least significant bit
M	
MA	Multiplexed access/multiple access
MAC	Media access control
MAN	Metropolitan-area network
MAU	Medium attachment unit
Mb or Mbit	Megabit (1 000 000 bits)
MCI	Management and control interface

MDI	Medium-dependent interface
MDU	Multidwelling units – apartment buildings and condominium
MFD	Mode-field diameter
MH	Mode-hopping
MIB	Management information base
MID	Multiplexing identification
MII	Media-independent interface
MLM	Multilongitudinal mode (laser)
MLT-3	Multiple-level transition – 3 levels
MM	Multimode
MMF	Multimode fiber
MPCP	Multipoint (media access) control protocol
MPCPDU	Multipoint control protocol data unit
MPEG	Motion picture experts group – ISO standards group dealing with video and audio compression
MPEG-2	MPEG-2 - ISO/IEC 13818-x series specifications
MPLS	Multiprotocol label switching
MPMC	Multipoint MAC (media access control) control
MPN	Mode-partitioning noise
MPO	Multifiber push on (connector)
MPOA	Multiprotocol over ATM
MSB	Most significant bit
MSO	Multiple (cable) systems operator
MTBF	Mean time between failures
MTP	Multiple terminations, push-pull latch (fiber optic connector)
MTRJ	MT ferrule, register jack latch (fiber-optic connector)
MTTR	Mean time to repair
MU	Miniature unit (fiber optic connector)
MWM	Multiwavelength meter
N	
NF	Noise figure (noise from an EDFA spontaneous emission in dB) Network flow (Ethernet)
NLE	Non-linear effects
NSP	Network service provider
NUT	Network under test
O	
OAM	Operation, administration and maintenance
OAN	Optical access network

OC	Optical carrier
ODN	Optical distribution network
ODU	Optical distribution unit
OLT	Optical line terminal/termination
OLTS	Optical loss test set
OMA	Optical modulation amplitude
OMCI	ONT management and control interface
ONT	Optical network terminal/termination (ONU connected to user service interface)
ONU	Optical network unit (connected to user service interface)
OOS	Out of service
OPM	Optical power meter
ORL	Optical return loss
OSA	Optical spectrum analyzer
OSC	Optical service channel
OSI	Open-systems interconnection
OSNR	Optical signal-to-noise ratio
OSP	Outside plant
OTDR	Optical time-domain reflectometer/reflectometry
P	
P2MP	Point-to-multipoint
P2P	Point-to-point
PAD	Padding field
Pb or Pbit	Petabit (1 000 000 000 000 000 bits)
PBX	Private-branch exchange
PC	Polished connector Personal computer
PCS	Physical coding sublayer
PDL	Polarization-dependent loss
PDU	Protocol data unit
PHB	Per-hop behavior
PHY	Physical-layer entity – part of the physical layer between the MII and MDI, as defined in IEEE Std. 802.3-1998
PIN	Positive-insulator-negative – type of optical detector
PLC	Planar lightwave (or lightguide) circuit
PLOAM	Physical-layer operation administration and maintenance
PMA	Physical-medium attachment sublayer
PMD	Physical-medium-dependent sublayer

PNNI	Private network-to-node (or network) interface
PON	Passive optical network
POP3	Post-office protocol version 3 – permits workstations to dynamically access a maildrop on a server host (TCP/IP)
POTS	Plain old telephone service
PPD	Partial packet discard
PPP	Point-to-point protocol
PPV	Pay-per-view
PRBS	Pseudo-random bit stream
PSB	Pulse suppressor box
PSTN	Public switched telephone network
PT	Payload type (ATM)
PTI	Payload type indication
Q	
QoS	Quality of service
R	
RBOC	Regional Bell operating company
RF	Radio frequency
RFC	Request for comments.
RFP	Request for proposal
RFQ	Request for quotation
RLEC	Rural local-exchange carrier
RMS	Root mean square
RPR	Resilient packet ring
RS	Reconciliation sublayer Reed-Solomon (FEC code)
RT	Remote terminal
RTT	Round-trip time
RT-VBR	Real-time VBR
Rx	Receiver
S	
SAL	Service-level agreement
SAR	AAL segmentation and reassembly (ATM)
SBS	Stimulated Brillouin scattering
SC	Subscription channel
SDH	Synchronous digital hierarchy
SDU	Service data unit
SEAL	Simple and easy adaptation layer

SES	Severely errored seconds
SLA	Service-level agreement
SLM	Single longitudinal mode (laser)
SM	Singlemode
SMF	Singlemode fiber
SN	Sequence number
SNI	Service network interface
SNP	Sequence number protection, comprised of CRC and EPC
SNR	Signal-to-noise ratio
SOHO	Small office/home office
SONET	Synchronous optical network
SPC	Super-physical-contact/super-polished connector
SSCS	Service-specific convergence sublayer
ST	Straight-tip (fiber-optic) connector
T	
Tb or Tbit	Terabit (1 000 000 000 000 bits)
TC	Transmission convergence (ATM)
TCP	Transmission control protocol
TCP/IP	Transmission control protocol/Internet protocol
TDM	Time-division multiplexing
TDMA	Time-division multiple access
TFF	Thin-film filter
TFP	Termination flow point
TIA	Telecommunications Industry Association (www.tiaonline.org)
TLR	Transport link rate
TLS	Transparent LAN service
ToS	Type of service
TR	Transport rate
Tx	Transmitter
U	
UBR	Unspecified bit rate
UGN	User group network
UI	Unit interval
UNI	User network interface
UPC	Ultra-physical-contact/ultra-polished connector
UUI	User-to-user indication
V	
VBR	Variable bit rate

VC	Virtual circuit
VCC	Virtual channel connection
VCI	Virtual channel identifier
VDS	Video distribution service
VDSL	Very-high-speed digital subscriber line
VFL	Visual fault locator
VLAN	Virtual LAN
VOD	Video-on-demand
VoIP	Voice over Internet protocol
VPCI	Virtual path channel identifier
VPI	Virtual path identifier
VPN	Virtual private network
W	
WDM	Wavelength-division multiplexing
WLAN	Wide-area LAN
WPON	Wavelength-division multiplexing PON
WWDM	Wide wavelength-division multiplexing
xDSL	Generic digital subscriber line
λ	Wavelength

Chapter 9

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The following organizations are involved in the development of standards for FO telecommunication networks and related products:

- ITU-T
- IEC
- IEEE
- TIA/ANSI and Telcordia (USA
- CENELEC/ETSI, EU and JIS (Japan)

ITU-T and IEEE have and are still publishing documents for FTTH PON transport level while the others are starting to address the issues at product level. More specifically, this refers to product specifications, performance, interface, reliability, and test method standards.

9.1 ITU-T Recommendations

9.1.1 PON-related Recommendations

G.982: Optical access networks to support services up to the ISDN primary rate or equivalent bit rates

G.983.1: Broadband optical access systems based on Passive Optical Networks (PON) (Oct. 1998)

- Called B-PON
- Protocol: ATM-PON
- Incorporates G.983.1 (1998)
- Option 1 – Symmetric 155.52/155.52 Mb/s
- Option 2 – Asymmetric 155.52 Mb/s upstream and 622.08 Mb/s downstream (Nov. 2001)
- Amendment 1: Option 3 – Symmetric: 622.08/622.08 Mb/s (Nov. 2001)
- Corrigendum errata (2002)
- Amendment 2: Optional, improved security mechanism, and 1244.16 Mb/s downstream (Mar. 2003)
- Implementers' guide for G.983.1 B-PON (Oct. 2003)

Consolidated Version G.983.1 (Dec. 2004) – Includes all of the above

- Amendment 1: Appendices V and VI - PICS (Protocol Implementation Conformance Statement) for OLT and ONU in G.983.1 (May 2005)

G.983.2: ONT management and control interface specification for B-PON (Jun. 2002)

- Revision 1 (Oct. 2002)
- Amendment 1 on Product identification, ONT-supported level of security, DS3 Circuit Emulation Service (CES), Performance monitoring, POTS support (Mar. 2003)

- Implementer's guide (2003); now in G.Imp983.2 Implementors' Guide to G.983.2 (2002)
- Amendment 2 on transport and management of video return path function for G.983.1 and G.983.3 B-PON transport system and G.983.2 ONT Management and Control Interface (OMCI) (Dec. 2004)
- Revision 2 on consolidation of Revision 1 and Amendment 1 and Amendment 2 and Implementer's guide and G.983.6 (20002), G.983.7 (2001), G.983.8 (2003), G.983.9 (2004), G.983.10 (2004) and minor corrections, clarifications, and augmentation of functions (May 2005)

G.983.3: A broadband optical access system with increased service capability by wavelength allocation (Mar. 2001)

- Amendment 1 on requirements for isolation and return loss because of the power budget changes needed for 622.08 Mb/s upstream rate (Jun. 2002)
- Amendment 2 on new appendix establishing the industry best practice optical budgets for B-PON system operating at 622 Mb/s downstream, 155 Mb/s upstream (May 2005)

G.983.4: A broadband optical access system with increased service capability using dynamic bandwidth assignment (DBA) (Nov. 2001)

- Amendment 1 on Appendix A: Performance monitoring parameters for requirements and specifications for performance monitoring function in Dynamic Bandwidth Assignment (DBA) (Aug. 2003)
- Corrigendum 1 (Dec. 2004)

G.983.5: A broadband optical access system with enhanced survivability (Jan. 2002)

G.983.6: ONT management and control interface specifications for B-PON system with protection features (Jun. 2002)

- Included in G.983.2 Revision 2 (May 2005)

G.983.7: ONT management and control interface specification for dynamic bandwidth assignment (DBA) B-PON system (Nov. 2001)

- Included in G.983.2 Revision 2 (May 2005)

G.983.8: B-PON OMCI support for IP, ISDN, video, VLAN tagging, VC cross-connections and other select functions. Gigabit-capable Passive Optical Networks (G-PON): General characteristics (Mar. 2003)

- Included in G.983.2 Revision 2 (May 2005)

G.983.9: B-PON ONT management and control interface (OMCI) support for wireless local-area network interfaces (Feb. 2004)

- Corrigendum: new summary on OMCI specification to support management of IEEE 802.11 interfaces

- Included in G.983.2 Revision 2 (May 2005)

G.983.10: B-PON ONT management and control interface (OMCI) support for digital subscriber line interfaces (Feb. 2004)

- Included in G.983.2 Revision 2 (May 2005)

G.984.1: Gigabit-capable passive optical networks (GPON): General characteristics for Gigabit-capable Passive Optical Networks (G-PON) (Mar. 2003)

G.984.2: Gigabit-capable passive optical networks (G-PON): Physical Media Dependent (PMD) layer specification (Mar. 2003)

G.984.3: Gigabit-capable passive optical networks (G-PON): Transmission convergence layer specification (Oct. 2003)

- Amendment 1: Editorial changes and technical improvements

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- Amendment 1: Managed entity relation diagrams for ONT, user traffic, MAC bridged LAN, structured CES, 1+1 protection, 1:1 protection and clarifications to managed entity identification attributes

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9.1.2 Other Useful Recommendations

G.652: Characteristics of a single-mode optical fiber and cable (2003, in revision)

G.671: Transmission characteristics of optical components and subsystems (2002)

9.2 Useful PON-Related IEC Standards

IEC 60793-2-50 Ed. 2: Sectional specification for category B single-mode fibers

IEC 60875-1: Non-wavelength-selective fibre-optic branching devices--Part 1: Generic specification

IEC 61300-3-7: Basic test and measurement procedures–Part 3-7: Examinations and measurements - Wavelength dependence of attenuation and return loss

IEC 61753-1-2: Fibre-optic interconnecting devices and passive components performance standard–Part 1-2: General and guidance – Passive components

IEC 62074-1: Fibre-optic WDM devices – Part 1: Generic specification

IEC 62149-5 Ed. 1.0: Fibre-optic active components and devices – Performance standards - Part 5: ATM-PON transceivers with LD driver and CDR ICs

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9.4 Telcordia

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GR-63, NEBS Requirements: Physical Protection GR-326, Generic Requirements for Singlemode Optical Connectors and Jumper Assemblies

GR-326, Generic Requirements for Fiber-Optic Connectors

GR-449, Generic Requirements and Design Considerations for Fiber Distributing Frames

GR-487, Generic Requirements for Electronic Equipment Cabinets

GR-771, Generic Requirements for Fiber-Optic Splice Closures

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GR-1081, Generic Requirements for Field-Mountable Optical Fiber Connectors

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A unique industry reference for the deployment and maintenance of PONs

CORPORATE HEADQUARTERS
400 Godin Avenue, Quebec City, Quebec
G1M 2K2 CANADA
Tel.: 1 418 683-0211
Fax: 1 418 683-2170

EXFO AMERICA
3701 Plano Parkway, Suite 160
Plano, TX 75075 USA
Tel.: 1 800 663-3936
Fax: 1 972 836-0164

EXFO ASIA
151 Chin Swee Road, #03-29
Manhattan House
SINGAPORE 169876
Tel.: +65 6333 8241
Fax: +65 6333 8242

EXFO CHINA
Tower C, Beijing Global Trade Center
Room 1207
36 North Third Ring Road East,
Dongcheng District
Beijing 100013 P. R. CHINA
Tel.: +86 (10) 5825 7755
Fax: +86 (10) 5825 7722

EXFO EUROPE
Omega Enterprise Park, Electron Way
Chandlers Ford, Hampshire
S053 4SE ENGLAND
Tel.: +44 2380 246810
Fax: +44 2380 246801

EXFO NETHAWK
Elektroniikkatie 2
FI-90590 Oulu FINLAND
Tel.: +358 (0)403 010 300
Fax: +358 (0)8 564 5203

EXFO SERVICE ASSURANCE
270 Billerica Road
Chelmsford, MA 01824 USA
Tel.: +1 978 367-5600
Fax: +1 978 367-5700

info@EXFO.com
www.EXFO.com

US$69.95

Fiber-optic telecommunications began generating interest in the late 70s, but it wasn't until the mid-90s that the real breakthough occurred. The optical amplifier and narrowband filter, for example, were the basis of WDM and DWDM, which would become some of the biggest buzzwords of all time. Indeed, the era of wavelength- and dense wavelength-division multiplexing was born and it would change the telecommunications world forever.

The success of these innovations caused a tremendous increase in communication traffic and, consequently, constant bandwidth demand and growth. This quickly led service providers to respond by bringing the optical fiber closer and closer to the premises, and finally to the premises itself and directly to home. New buzzwords —FTTx and PON— have emerged and a new era is beginning.

Telecom engineers, technicians, managers and scholars alike will find in this book a detailed review of what has been done so far in this relatively new area of expertise, including all technical aspects, specifications, and performance requisites of the passive optical network. It also covers the different types of PONs (broadband, Gigabit-capable and Ethernet-ready) and, for each type, discusses, the optical and protocol network layers in great detail. In addition, related testing requirements and solutions are presented and illustrated not only from the point of view of the network service provider, but also from the installers and maintainers' standpoint. Finally, the reader will also find a list of available international standards, as well as useful definitions and acronyms.

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