Passive Optical Networks and FTTx: Technology and Solutions

By

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Abstract

Competition for delivering high-bandwidth "multi-play" services (video, voice, data) is on constant increase. Advanced service delivery requires a higher bandwidth pipe to the end user through passive optical network (PON) technologies.

The two major PON standards GPON is an International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) and EPON is a standard developed by the Institute of Electrical and Electronics Engineers (IEEE).

This project compares and looks at the choices and challenges service providers face as they bring new PON technology possibilities to their customers and analyze these two standards in terms of their performance, physical properties, implementation and testing requirements. It also discusses the evolution paths for each of the standards and the challenges for such evolution. The final chapter will include the conclusions, some final thoughts, suggestions and recommendations for new projects implementation.

Acknowledgements

Words are often too less to reveal one's deep regards. An understanding of the work like this is never the outcome of the efforts of a single person. I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this project paper.

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No words of thanks are enough for my dear parents and family whose support and care makes me stay on earth.

At the end, I would like to thank all the faculty members of the department and all my friends who directly or indirectly helped me in completion of this project.

Dedication

I dedicate this project to my wife, Ani, and Parents for the understanding and encouragement they provided during the two years of my Masters study.

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List of Abbreviations

Alen	ATM (partition) length
Alloc-ID	Allocation Identifier
APON	ATM over Passive Optical Networks
ATM	Asynchronous Transfer Mode
BER	Bit Error Ratio
BIP	Bit Interleaved Parity
BPON	Broadband Passive Optical Networks
Blen	BWmap Length
BWmap	Bandwidth Map
CLP	Congestion Loss Priority
CRC	Cyclic Redundancy Check
DBA	Dynamic Bandwidth Assignment
DBRu	Dynamic Bandwidth Report upstream
DEMUX	Demultiplexer
DSL	Digital Subscriber Line
EPON	Ethernet Passive Optical Network
FEC	Forward Error Correction
FTTB	Fiber to the Building
FTTB/C	Fiber to the Building/Curb
FTTC	Fiber to the Curb
FTTCab	Fiber to the Cabinet
FTTH	Fiber to the Home
GEM	GPON Encapsulation Method
GMII	Gigabit-Medium-Independent-Interface
GPM	GPON Physical Media (Dependent)
GPON	Gigabit Passive Optical Network
GTC	GPON Transmission Convergence
HEC	Header Error Control
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
LCF	Laser Control Field
LLC	Logical Link Control layer
LLID	Logical Link Identifier

LSB	Least Significant Bit
MAC	Media Access Control
MDI	Media-Dependent-Interface
MDU	Multi-Dwelling Unit
MIB	Management Information Base
MII	Media-Independent-Interface
MPMC	Multi-Point-MAC-Control
MPCPDU	Multi-Point-MAC-Control Protocol-Data-Unit
MSB	Most Significant Bit
MUX	Multiplexer
NRZ	Non-Return-To-Zero
NT	Network Termination
OAM	Operation, Administration and Maintenance
OAN	Optical Access Network
ODN	Optical Distribution Network
OLT	Optical Line Termination
OMCI	ONU Management and Control Interface
ONT	Optical Network Termination
ONU	Optical Network Unit
OSI	Open System Interconnection
P2MP	Point to Multi Point
P2P	Point to Point
PCBd	Physical Control BLock downstream
PCS	Physical-COding-Sublayer
PDU	Protocol Data Unit
Plend	Physical Length downstream
PLI	Payload Length Indicator
PLOAM	Physical Layer Operations, Administration and Maintenance
PLOAMd	PLOAM downstream
PLOAMu	PLOAM upstream
PLOu	Physical Layer Overhead upstream
PLSu	Power Leveling Sequence upstream
PMA	Physical-Medium-Attachment layer
PMD	Physical-Medium-Dependent layer
PON	Passive Optical Network
Port-ID	Port Identifier
Psync	Physical Synchronization

PT	Payload Type
PTI	Payload Type Indicator
QoS	Quality of Service
RS	Reconciliation
SCB	Single Copy Broadcast
SDH	Synchronous Digital Hierarchy
SNI	Service Node Interface
STM	Synchronous Transfer Mode
TC	Transmission Convergence
T-CONT	Transmission Container
UNI	User Network Interface
UTP	Unschielded Twisted Pair
VCI	Virtual Channel Identifier
VoATM	Voice over ATM
VoIP	Voice over IP
VP	Virtual Path
VPI	Virtual Path Identifier
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing

Chapter 1

1. Introduction

It is all about the bandwidth. With the increased need for higher bandwidth to support the triple play services (voice, data and video) optical transmission is getting more popular in the access network. The access network must evolve to support all possible services from high speed internet to HDTV.

The main driver behind the Internet traffic growth is video traffic. A clear business orientation is required along with short ROI (Return On Investment) from CAPEX (Capital Expenditure) so that Telecom or Cable Operators could upgrade their access network. Two primary players for networking standards are IEEE (Institute of Electrical and Electronics Engineers) and ITU (International Telecommunications Union). The problem is which one to choose when establishing a new access network.

Some cable operators still have strong interest in RFoG solutions. RFoG, uses passive optical technology to split signals from a single fiber across fiber connections to multiple premises. GPON uses the baseband digital multiplexing and other telecom PON solutions, while RFoG allows operators to extend amplitude-modulated laser signals all the way to the premises, thereby eliminating the need to replace legacy headend and customer equipment. I wouldn't say all cable operators are looking at all-fiber networks at this point, but they do want to use fiber where it makes sense in wireless backhaul, rural and greenfield residential, commercial and other areas. I believe the industry is going through a transition period that is leading to all-fiber architectures based on PON-like technologies if we apply Moore's Law to bandwidth growth.

1.1. PON Systems

A PON consists of an optical line termination (OLT) at the central office and a number of optical network terminals (ONTs) at the end user locations, along with all of the intervening fibers, splitters, etc., which collectively are called the optical distribution network (ODN). In general, PONs offer a cost advantage over AON (Active Optical Networks). PON allows carriers to deploy distribution fibers deep into the neighborhood. Passive optical splitter is then used to broadcast the signal via individual fiber strands to up to 64 homes. Passive optical splitter does not require power, which lowers both deployment and operating costs. GPON downstream operation rate of 2.5 Gbits/sec and 1.25 Gbits/sec upstream. GPON is designed for optimal efficiency in terms of revenue bandwidth; operations, administration, and maintenance (OAM); scalability; and support for multiple services. In parallel, the IEEE has defined Ethernet PON (EPON), using a similar point-to-multipoint network topology and a Multi-Point Control Protocol (MPCP) to communicate between the OLT and optical network units (ONUs).

1.2. Motivation

PON standardization activities have been going on for a couple of years now. With the continuing availability of more advanced technology, PON line rates have increased from 155Mbps up to 2.4Gbps.

With the explosion of the Internet previous PON systems proved to be very inefficient. This created the opportunity for the development of the pure-Ethernet based EPON, taking advantage of emerging QOS-aware GigE switches and cost-effective integration with other Ethernet equipment. Ethernet has proven over time to be the ideal transport for IP traffic.

As a result, the IEEE 802.3 tasked the 802.3ah "Ethernet in the First Mile" work group with the development of standards for point-to-point and point-to-multipoint access networks, the latter specifying Ethernet PONs. EPON is currently part of standard Ethernet.

Development of the Gigabit-capable Passive Optical Network (GPON) standard (G.984 series) really started after proposals by FSAN members for a protocol-independent ATM/Ethernet Gbps PON solution were not very popular within the IEEE 802.3ah work group. FSAN then decided to continue this as a different competing standard in the ITU.

EPON is meant to deliver Ethernet services exclusively as opposed to GPON, which is designed to handle multiple protocols. But leading cable strategists appear to feel EPON offers the best long-term PON migration path for cable, starting with initial applications in high-end commercial services.

Do we really need GPON next to EPON? In order to answer this question I will take a closer look at these two flavors, and compare their different approaches on technical and practical merits.

1.3. PON Technical Considerations

PON is a technology that offers shared optical fiber to deliver services like voice, video and data. Passive splitters are used to share fiber among subscribers. That means no electronics in the outside plant. Today's TDM-PON based on BPON, EPON, or GPON use two critical devices: an Optical Line Terminal (OLT), which is typically located in the central office (CO), and an Optical Network Terminal (ONT), which is located at the customer premises. A single fiber connects the OLT with the neighborhood node, where the signal is split typically into 32 fibers, each feeding an ONT. [5]

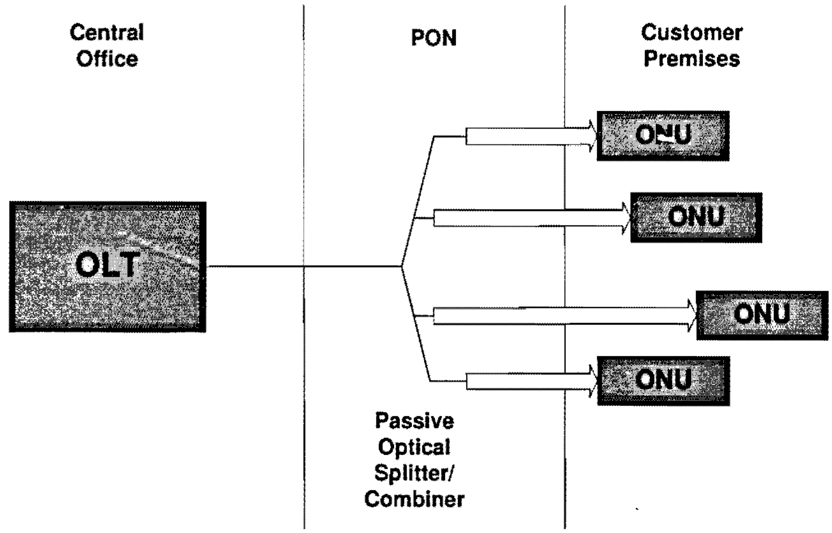


Figure 1: PON Architecture

Any PON (xPON) in the local loop has:

- 1 fiber
- Minimum fibers/space in CO
- N+1 optical transceivers
- No electrical power in field
- Passive Optical Splitter/Combiner

TDM-PON has upstream and downstream signals separated by wavelengths (1.3μm/1.49μm). Optionally 1.55μm is reserved to carry broadcast analog video signal.[5]

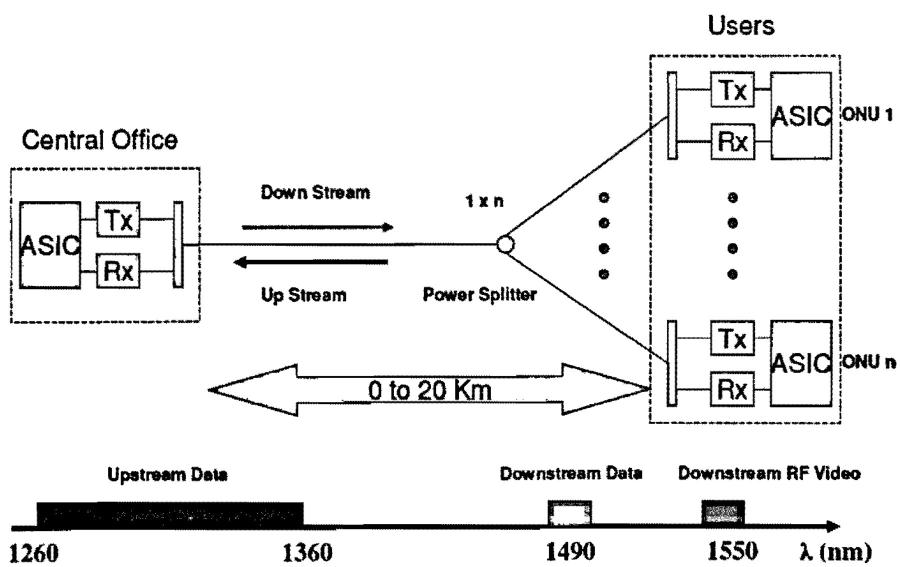


Figure 2: TDM-PON Basics

1.4. PON Critical Issues

In designing an access network, issues of reliability are of the same importance as cost effectiveness. In most PON applications the downstream and upstream optical signals are carried over the same fiber. Using different wavelengths for the downstream and upstream signals reduces the total optical loss of the PON and for this reason it is the most commonly used technique. Signals are inserted or extracted from the fiber using a coarse wavelength division multiplexer (CWDM) filter at the CO and subscriber premises. An optical diplexer is a device specifically designed for PONs that combines the laser transmitter, the photodiode receiver, and the CWDM filter into a single package. Diplexers used at the CO have a 1490 laser and a 1310 receiver. Diplexers used at the subscriber premises have a 1310 laser and a 1490 receiver. A PON can also carry a broadband overlay on a third wavelength. This wavelength overlay is typically used to transport RF video at 1550 nm. Unlike the baseband signal, the broadband overlay is an analog signal. For this reason the optical power of the wavelength overlay is roughly 100 times greater than the baseband signal. Several issues arise because of this and below are a summary to PON critical issues [5]:

Optical issues:

Absorption/Attenuation:

- Fiber (only 1310 nm)
- Splitter/coupler.

Dispersion (1490/1550 nm):

- MLM FP Laser vs. SLM DFB
- Chromatic, only 2.5+ Gbps
- PMD, only 10+ Gbps

Non-Linear Effects:

- Only 1550nm High Power.

Mechanical Issues:

Bending:

- Critical at longer λ, 1550nm

Connection/Joints:

- Connector Cleanliness.

Workmanship:

- Fusion Splices.

PON components for the most two implemented PON technologies (GPON and EPON):

EPON:

- FP Laser
- PIN detectors
- 1:N splitters
- Diplexers and triplexers
- Bust-mode receivers.

GPON:

- DFB laser diodes
- APD's

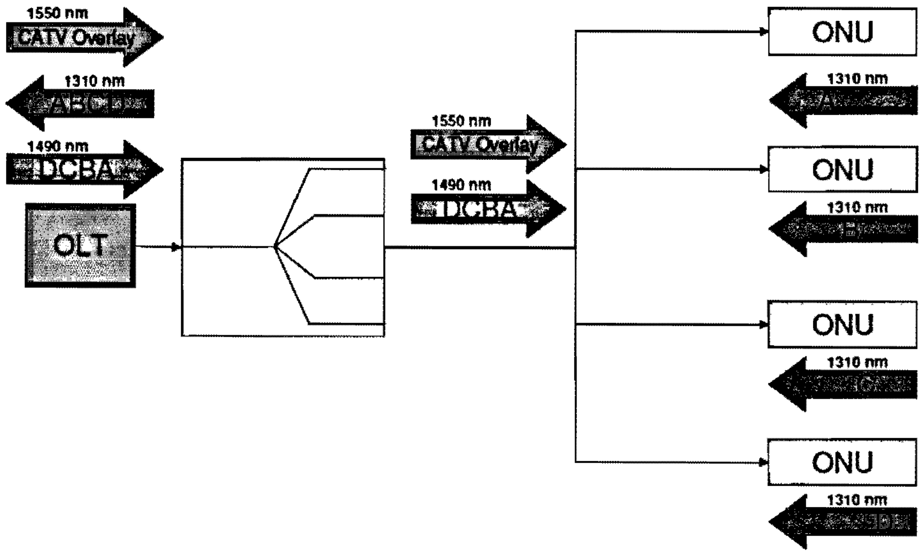


Figure 3: PON Protocol Overview

Another issue is the protection level. Many neighborhoods consist of a mixture of residential homes and small businesses. Several types of redundancy for high reliability are available, but it seems to be impossible task trying to provide both economical residential and resilient business service from the same network. The network needs to be carefully planned and engineered before services are offered. ITU-T specifies four types of protected PON networks while IEEE does not specify any [7], [11]:

1. Spare fiber between the OLT and the splitter.
2. Full duplication of the FTTx system.
3. Redundant OLT system
4. Independent duplication of branch line and common lines.

1.5. PON Advantages / Disadvantages

PON technology offers a lot of benefits some of which are listed below:[18]

- Future Proof – there are no active field electronics to replace when upgrading.
- High bandwidth.
- Delivers multiple services (Voice, Data, Video).
- Protocol independent (IP, TDM, ATM).
- Scalable.
- Multi-topology (P2P, P2MP, Ring, Mesh)
- Digital and Analog capable.
- Amplification not required.
- Low maintenance and operating cost.
- Cost – competitive with low bandwidth copper networks.
- Long economic life.

Some of the PON disadvantages are:

- Splitters have a static configuration. Hence management is only possible at the termination points [1], [2], [3].
- P2MP topology configurations all information is broadcasted in the downstream direction to all users which can be a security problem [1], [2], [3].
- Physical reach is limited due to the fact that no active components exist between the CO and the end user. Power at the CO has to be enough to serve at least 64 users. Ranging procedure also limits the physical reach of a PON [1], [2], [3].
- When network and sub-networks are upgraded, the whole network should be down to modify.
- Band usage limits the number of users on one PON network because of the shared fiber between the provider and the users.

1.6. Research Problem

Many PON standards exist, but the problem is which one to choose when implementing a new project. This project compares GPON versus EPON solutions and demonstrates which technology provides a compelling business case for access deployment, support for different services on a single fiber, to a large number of end users covering a broad network reach. Industry standards for Passive Optical Network (PON) technology have enabled the initial deployment of Fiber to the Premise (FTTP) services. Regardless of any technology merits, this project makes a simple comparison to determine the similarities and the differences between EPON and the emerging ITU-T GPON for a given FTTx network.

1.7. Thesis Outline

Chapter-2 will discuss in details standardization in Passive Optical Networks with focus on EPON and GPON standards. Chapter-3 will be a comparison between standards and a detailed qualitative comparison of EPON and GPON along with graphs. Chapter-4 will deal mainly with implementations and recommendations for any new project and will discuss the integration, test and management of PON networks. It will also discuss types of optical fibers cables used in the optical distribution network. Chapter-5 will discuss the available evolution paths for EPON and GPON and the challenges they face in such evolution. Chapter-6 will be the final conclusion, recommendation and final thoughts.

Chapter 2

2. Standardization of Passive Optical Networks

Two primary players for networking standards are:

- IEEE (Institute of Electrical and Electronics engineers)
- ITU (International Telecommunications Union)

In late 1990's a group of operators was formed with the objective "Global Domination of the Fiber Access Market". The group called itself FSAN (Full Service Access Network". This group develops all PON standards prior to submission to the ITU. The ITU-T released a standard called "Gigabit-capable Passive Optical Net- work" (GPON) (G.984.x 2003). The IEEE released a standard which is known as "Ethernet Passive Optical Network" (EPON) (802.3ah 2004). Each standard describes the functionality of the first two layers of the "Open System Interconnection" (OSI) network model. Figure 4 shows the evolution of each of standard over time.

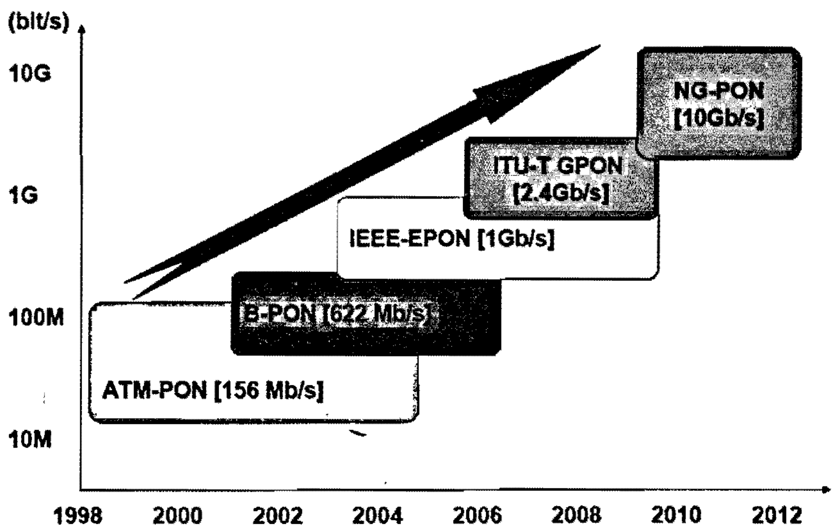


Figure 4: PON Standards Timeline

The two layers which are described by the standards have the following functionality:

• Layer 1 is the Physical layer which controls the transmission of raw bits over a communication link [4].

• Layer 2 is the Data link layer which decodes and encodes a packet into bits. It provides flow control and frame synchronization of packets besides providing reliable transit of data across a physical link.

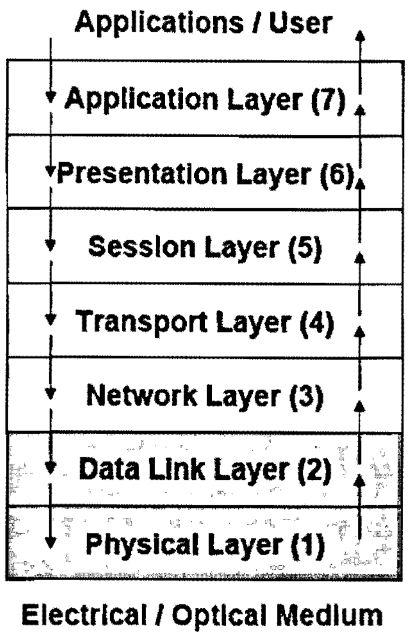


Figure 5: OSI Reference Model

2.1. EPON IEEE 802.3ah

EPON consists of a single, shared optical fiber connecting a service provider's central office to a passive coupler with no active elements in the path. The passive coupler is positioned not more than 1 Km from the end customer, to minimize fiber usage. PON networks have two standards, the 1000BASE-PX10 and 1000BASE-PX20. The number 10 and 20 refer to the maximum reach distance or the maximum distance (km) between sender and receiver [3]. The objective of these two standards is: a) P2MP on optical fiber, b) 1000Mbps for up to 10km on a single fiber for a 1:16 split ratio, c) 1000Mbps for up to 20km on a single fiber for a 1:16 split ratio and d) BER better than or equal to 10^{-12} at the PHY service interface.

2.1.1. EPON Stack

EPON stack is the adaptation of the P2MP topology where the "Multi-Point-MAC-Control" (MPMC) layer is added as shown below in figure 6 [12].

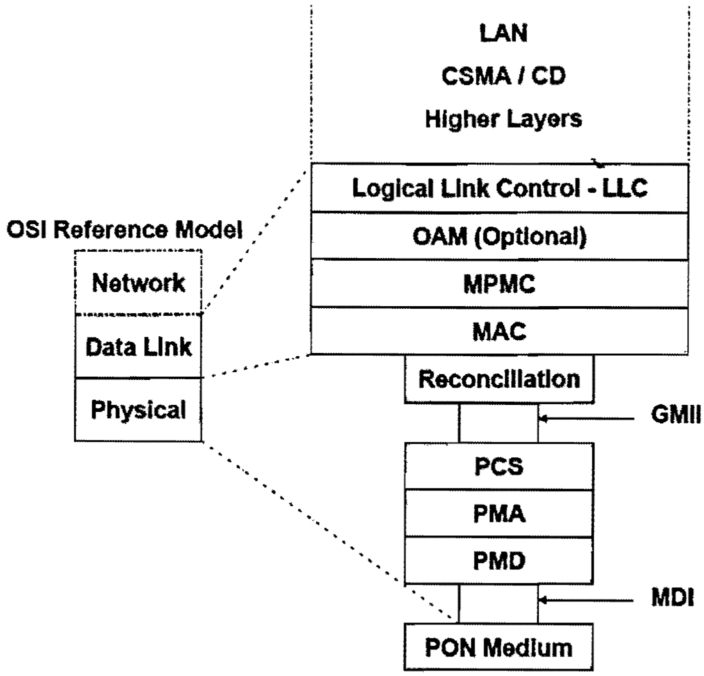


Figure 6: EPON Stack P2MP

2.1.2. EPON Layers

As shown in figure 6, the "Logical Link Control" layer (LLC), "Medium Access Control" layer (MAC) and "Multi-Point-MAC-Control" (MPMC) are part of the data link layer. The "Reconciliation" (RS), "Physical-Coding-Sub-layer" (PCS), "Physical-Medium-Attachment" layer (PMA), "Physical-Medium-Dependent" layer (PMD) are part of the Physical layer. The "Gigabit-Medium-Independent-Interface" (GMII) and "Medium-Dependent-Interface" (MDI) are two interfaces which are standardized and are access points for the other layers. A delay requirement is specified from the MDI to GMII in the standard. OLT implements the protocol stack different from the ONU. A PON fiber enters the system at the MDI lowest level which is a standardized connection point for the fiber and acts as an interface for the higher electrical circuit. Some physical characteristics are specified at the optical level, like maximum distance and transmission line speed. The standards 1000Base-PX10 and 1000Base-PX20 are divided into a "D" and "U" section, which refers to the Downstream and Upstream. Downstream is from OLT to ONU and upstream from ONU to OLT. The split-ratio is defined as 1:16 or 1:32 for both standards [12].

Name	Location	Rate (Mb/s)	Nominal Reach (Km)	Medium
1000Base-PX10-D	OLT	1000	10	One single-mode fiber PON
1000Base-PX10-U	ONU			
1000Base-PX20-D	OLT	1000	20	One single-mode fiber PON
1000Base-PX20-U	ONU			

Table 1: EPON Standards Characteristics (Split Ratio 1:16)

Layers above the MDI are used in the adaptation and conversion process. These layers are specifically designed to convert the physical medium to the GMII standardized interface. The layers responsible for this are, the "Physical-Medium-Dependent" layer (PMD), "Physical-Medium-Attachment" layer (PMA) and "Physical-Coding-Sub-layer" (PCS). The PMD layer controls the actual modulation of the data on the carrier which is a laser for PON networks. Different wavelength is used for the upstream and downstream direction as specified in 802.3ah and shown in the below table. At the PMD layer data from the PMA layer is modulated on the carrier. The demodulated data from the received carrier is forwarded to the PMA layer. The PMD Service Interface supports the exchange of 8B/10B code-groups between the PMA and PMD entities. The PMD translates the serialized data of the PMA to and from signals suitable for the specified medium [3], [12].

Description	1000Base-PX10-U	1000Base-PX10-D	1000Base-PX10-U	1000Base-PX20-D
Nominal transmit Wavelength	1310 nm	1490 nm	1310 nm	1490 nm
Transmit direction	Upstream	Downstream	Upstream	Downstream
Range	0.5 – 10 Km		0.5 – 20 Km	

Table 2: Physical Properties PMD

PMA layer takes care of serialization / deserialization of code-groups for transmission and reception during which the clock signal is retrieved from the incoming data which is 8B/10B coded. Data from the PMA will then be decoded in the upper PCS layer from 8B/10B data into standard-bytes or octets which are forwarded to the GMII. Any received octets from the GMII will then be encoded to 8B/10B coding. More about the 8B/10B coding could be found in reference [13]. During this 8B/10B encoding and decoding each octet is converted to a 10-bit value with certain number of zeros and ones in a frame to maintain DC balance. The side effect of this coding mechanism is a 25% increase of bandwidth. The layers PMD PMA and PCS are medium dependent. They are presented to the higher layers by the GMII to make them medium independent. GMII is a standard interface which in theory can be attached to any physical layer with a GMII interface. The reconciliation layer translates this standard interface and presents it to the MAC layer. EPON uses P2MP in stead of P2P connections. For EPON systems an extra layer of Multi-point MAC Control (MPMC) is placed on top of the standard MAC layer. The MAC layer is responsible for framing, addressing, error detection, access control and moving data to and from the interface. Both OLT and ONU have such a layer but with different behavior. ONU creates a single instance of this layer while the OLT creates multiple instances of this layer, each instance is related to a connected ONU. Broadcast messages at the OLT side has one special MAC for which all data sent to this MAC is broadcasted to all connected ONUs. This is called the "Single Copy Broadcast" (SCB). The MPCP layer can handle multiple underlying MAC instances as shown figure 12 page 28.
An optional "Operation, Administration and Maintenance" (OAM) client can be placed for management purposes on the top of the MPCP layer. Each MAC instance is identified by a so called "Logical Link IDentifier" (LLID) which is then used to route data to the corresponding MAC client based on their LLID

data packages. Each ONU and OLT tags their frames with a certain LLID, the ONU will discard this frame if the LLID does not matches or otherwise process it. At the ONU an individual MAC instance will do the same. The actual EPON intelligence is located in the MPCP. This MPCP at the OLT side is responsible for "Dynamic Bandwidth Allocation" (DBA), by reserving upstream slots and assign them to an ONU. Congestion reports from ONUs help to allocate the bandwidth in a PON network. In the downstream direction (point to multipoint), an EPON operates as broadcast and select network. The OLT uses the entire bandwidth of the channel to broadcast 802.3 Ethernet frames to all ONUs. Each ONU extracts those packets that contain the ONU's unique media access control (MAC) address. In the upstream direction (Multipoint to point), multiple ONUs share the transmission channel. Thus, the ONUs need to employ arbitration mechanism to avoid collisions. Each ONU transmits within a dedicated time slot and the OLT receives a continuous stream of collision-free frames from multiple ONUs. An ONU can have multiple LLIDs, each LLID represents a message queue [12], [3].

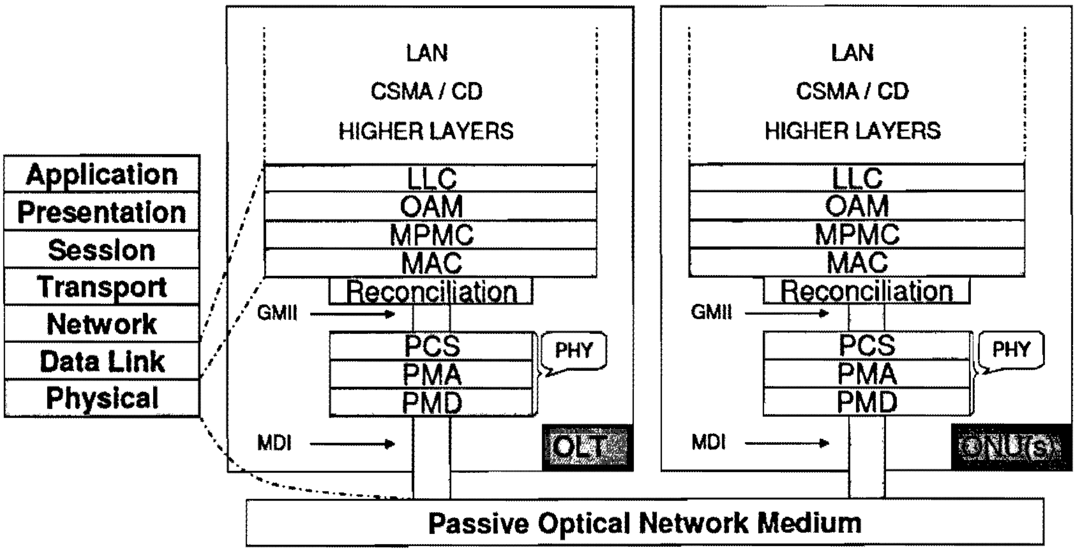


Figure 7: EPON Layering

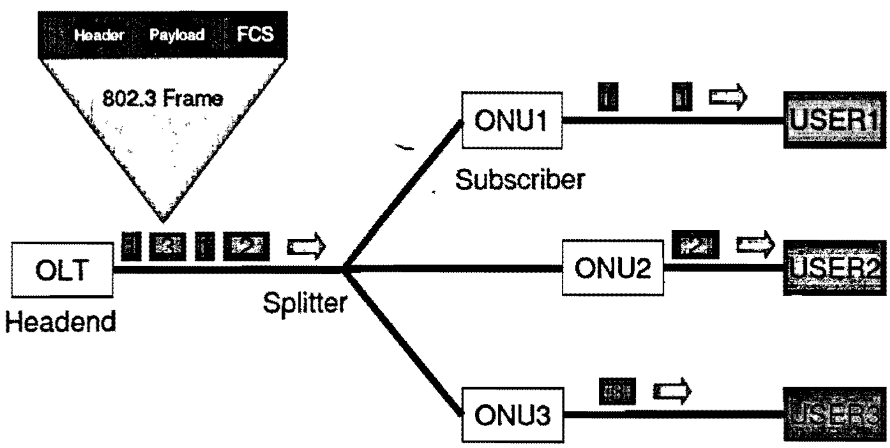


Figure 8: EPON Downstream

With two Ethernet control messages (GATE and REPORT), the OLT arbitrates the upstream transmissions by allocating an appropriate time slot/transmission window (TW) to each ONU. An ONU is only allowed to transmit during the TW allocated to it. The OLT assigns TW via GATE messages. Each ONU uses a set of queues to store its Ethernet frames and starts transmitting them as soon as its TW starts.

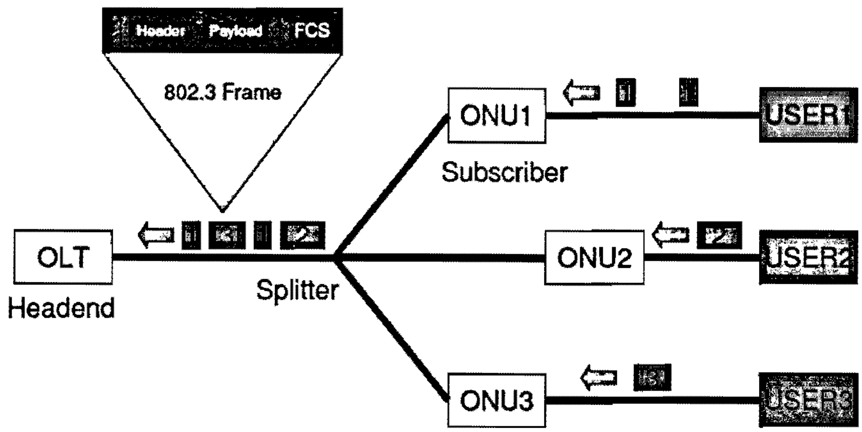


Figure 9: EPON Upstream

Within each cycle, ONUs use REPORT messages that are transmitted along with the data in the TW to inform the OLT about its bandwidth requirements. Between the TW of two ONUs there is a certain guard time needed to account for the laser on and off times, receiver recovery times, round trip delay and other optic related issues. Upon receiving a REPORT, the OLT passes the message to a dynamic bandwidth allocation (DBA) module, which performs the bandwidth allocation computation [3], [12].

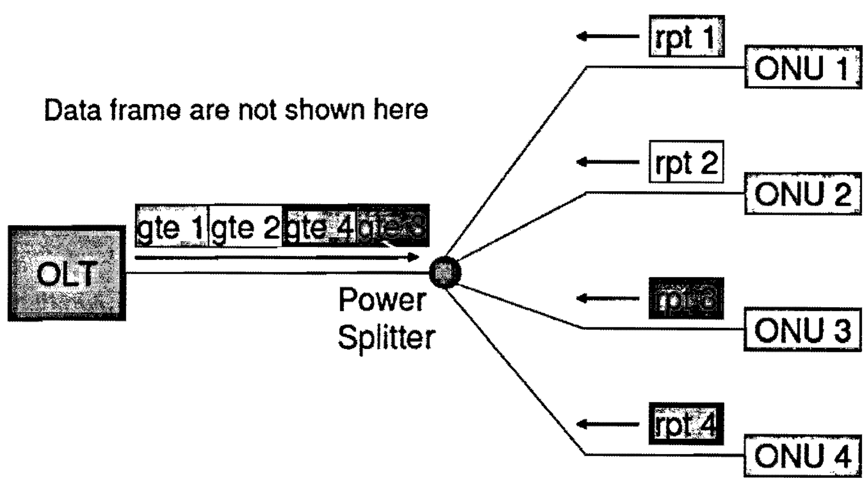


Figure 10: EPON Multi-Point Control Protocol (MPCP) – report / gate messages

2.1.3. EPON Frame Format

Two types of frames are recognized. The data frames needed to transport the user data and the control frames needed to configure the system. Access to the P2MP network is done via the MPCP. The control packages are filtered at the MPCP layer and are not forwarded to the upper layers. The control frames are identified by a certain OPCODE in the opcode field and which is 2 bytes. Gate, Report, Register Request, Register, and Register Acknowledge are different opcode values [12]. The register REQ, register and register ACK are used when the ONU is first connected to the OLT to negotiate and associate itself with the OLT [3].

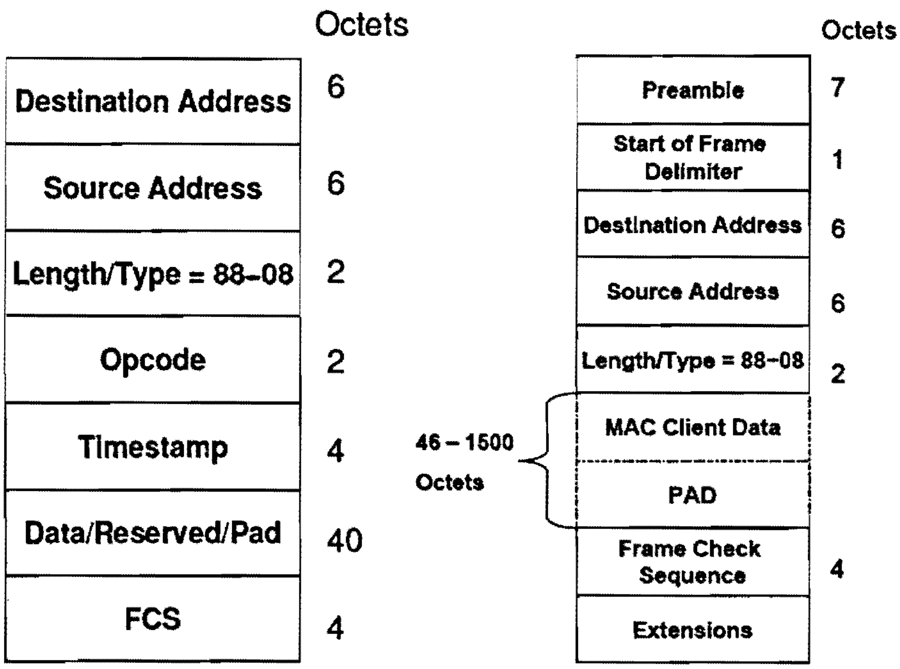


Figure 11: Multi-Point Control Protocol (MPCP) Control Frame (Left) and MAC-Frame (Right)

Like the standard Ethernet operation each Ethernet frame is transmitted with 8 bytes synchronization field called "Preamble" and "Start of Frame Delimiter" (SFD) in front of it as shown in the above Figure. EPON standard adds the standards MAC layer the MPCP layer which allows multiple MAC instances at the OLT. Each of these instances corresponds to a connected ONU identified by a LLID. Thus a virtual path is created between the OLT and the ONU which requires extra addressing parameters to route the received data to the corresponding MAC instance. For this purpose EPON uses the "Preamble/SFD" shown in figure 11. A field called "Start of LLID delimiter" (SLD), LLID and CRC8 are inserted into the preamble. The CRC8 value checks for transmission errors of field 3 to 7. For downstream data an ONU forwards frames with a valid LLID to the higher layers and discards other LLIDs. At the OLT each upstream frame is processed by the MAC instance which has the same LLID as the frame [3].

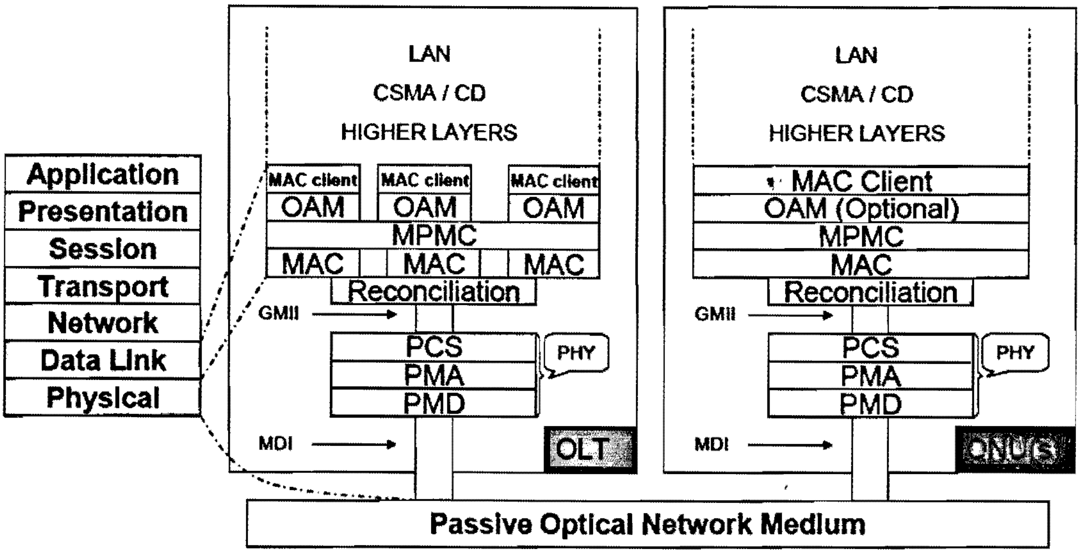


Figure 12: Relationship of the Multi-point MAC control and the OSI protocol stack

2.2. GPON ITU-T G.984.x

FSAN group developed a set of proposals which resulted in ITU standards G.984.x. These Gigabit PON (GPON) standards build on the set of G.983.x (BPON) and added new capabilities, some of which are:

- Extensions of splitting ratios to 1:64 and 1:128.
- Extensions to 2.488 Gb/s in both directions.
- Extended logical reach of 60 km
- Higher privacy and security through use of the Advanced Encryption Standard (AES) algorithm.
- A bandwidth-efficient new GPON Transmission Convergence 125-µs frame structure at Layer 2 within which ATM cells and new GPON Encapsulation Method (GEM) frames can both be combined. Then, within the GEM frames, synchronous telephony services (T1/E1 and DS-0) and data services such as Ethernet can be efficiently multiplexed.

GPON is intended to be a flexible protocol supporting residential and business needs in terms of bandwidth, services and both symmetrical and asymmetrical (downstream/upstream) gigabit capable passive optical network [1], [2].

2.2.1. GPON System Architecture

A GPON system consists of the three basic PON components, an OLT which is at the distribution side, an ONU at the user side and in between an ODN. The OLT can be divided into three components, a PON core shell, a cross connect shell and a service shell. The PON core contains the ODN interface function and the PON TC (Transmission Convergence) function [6]. The ODN function is a physical interface to the fiber network and which corresponds to the first layer of the OSI model [1], [10].

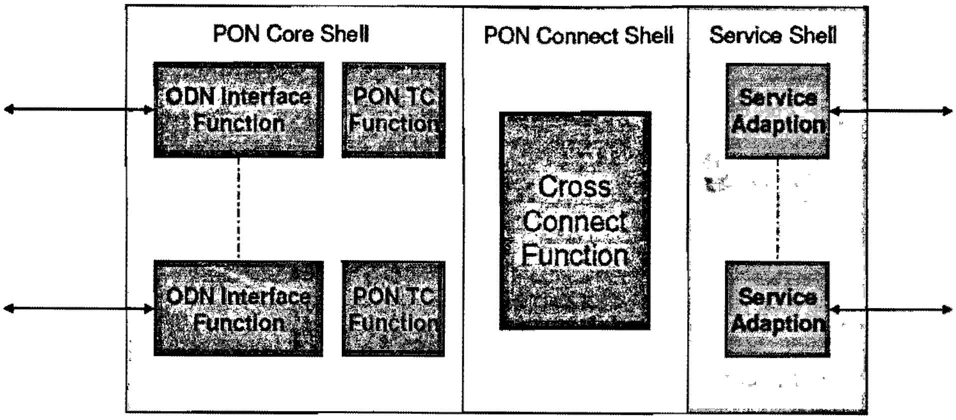


Figure 13: OLT Functional Block Diagram

An OLT can have multiple ODNs connected to it, each to serve one or more ONUs. The PON TC function is responsible for the following tasks:

- Framing
- "Media Access Control" (MAC)
- "Operations Administration and Maintenance" (OAM)
- "Dynamic Bandwidth Assignment" (DBA)
- Delineation of "Protocol Data Units" (PDUs) for the cross connect function, and ONU management

These functions are covered by the second layer of the OSI model. The Cross Connect shell connects the PON core shell and the Service shell. The service shell represents a client interface. ONU is installed at the user side and has a PON Core shell and Cross Connect shell as well. The interface function for the ONU is to connect the ONU to the OLT [6]. An ONU has standard one Optical interface but optionally can have a second one. A "Multiplexer" (MUX) and "Demultiplexer" (DEMUX) is used instead of a Cross Connect Shell to convert the PON core shell functions to the Service shell. The functions of this MUX and DEMUX are to multiplex and demultiplex several services to a single interface. The below figure shows the Physical layer, the TC layer and the Client interfaces. The optical transmission medium for the physical connection between the OLT and ONU is provided by the ODN (Optical distribution Network) which consists of the passive optical elements in the outside plant [1], [10].

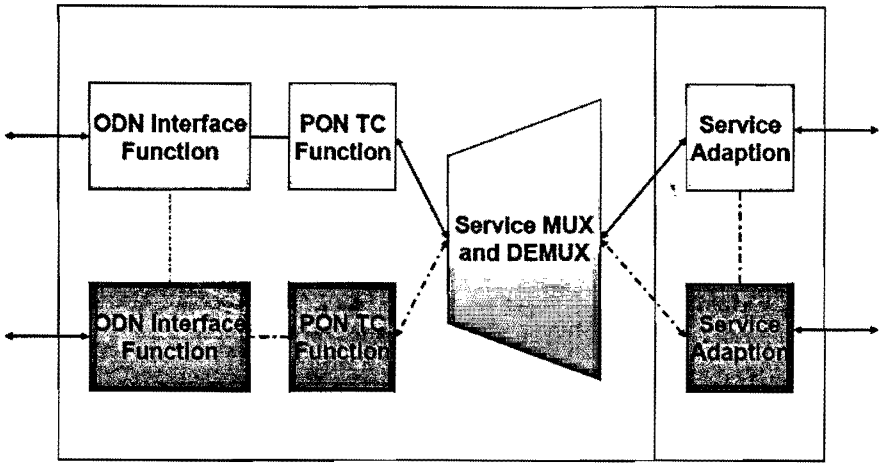


Figure 14: ONU Functional Block Diagram (Optional is shown in doted line)

2.2.2. GPON Physical Media Dependent (PMD) Layer

This layer is the interface to the optical fiber of an optical access network (OAN) and is represented by the ODN interface block. PMD has the capability of transporting different services between the user-network service (UNI) and the service node interface (SNI). Conversion from electrical to optical signals and vice versa is done at this layer. The transmission line rate is specified by the ITU-T as shown below.

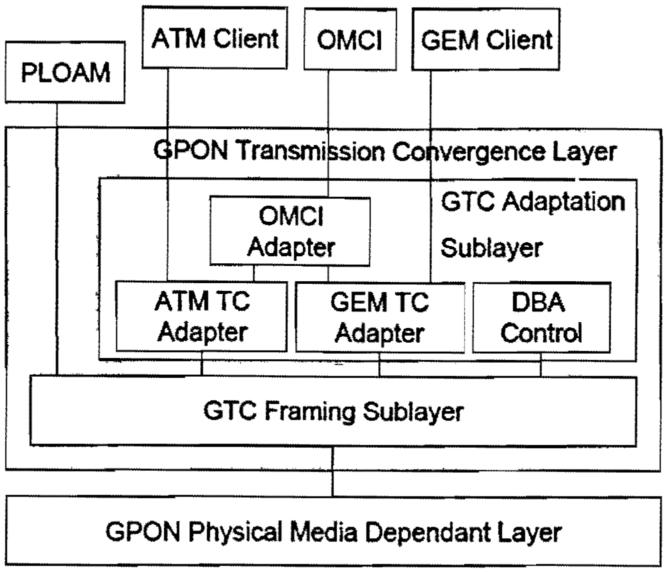
Upstream	Downstream
155.520 Mbit/s	1244.160 Mbit/s
622.080 Mbit/s	1244.160 Mbit/s
1244.160 Mbit/s	**1244.160 Mbit/s**
155.520 Mbit/s	2488.320 Mbit/s
622.080 Mbit/s	2488.320 Mbit/s
1244.160 Mbit/s	2488.320 Mbit/s
2488.320 Mbit/s	**2488.320 Mbit/s**

Table 3: GPON Transfer Speed (Multiple of 8KHz) Symmetric rates in bold

Two directions for optical transmission are recognized by the ODN, downstream and upstream, which can take place on the same fiber (duplex) or on separate fibers and components (simplex). The above bitrates can be transmitted on an optical carrier. The laser can operate at a certain wavelength with ranges defined by the ITU-T for upload and download transmission as in the below table [2].

	Upstream	Downstream
Single Fiber	1260 - 1360 nm	1480 - 1500 nm
Dual Fiber	1260 - 1360 nm	1260 - 1360 nm

Table 4: GPON Wavelength bands



PLOAM = Physical Layer Operations, Administration and Maintenance
OMCI = ONU Management and Control Channel
GEM = GPON Encapsulation Method
DBA = Dynamic Bandwidth Assignment
GTC = GPON Transmission Convergence
GPM = GPON Physical Media (Dependent)

Figure 15: GPON Stack Overview

The maximum logical reach between an OLT and an ONU is limited to 60 km and which is a theoretical distance limited by the implementation and hardware specifications. Difference in reach exists between OLT to ONU-x and OLT to ONU-y if multiple ONUs are connected to an OLT. This reach is called the differential logical reach and may not exceed 20 km due the maximum ranging window. The split ratio is standardized to 1:64, the TC layer supports up to 1:128 for future use. This ratio is limited by the output power of the OLT transmitter, path loss and the total amount of power divided by all connected users. To ensure enough power for each user, a certain maximum is specified. Above the physical layer the data packets are coded and decoded. The layer responsible for this is the "GPON Transmission Convergence" (GTC) layer. Downstream and upstream line code is NRZ coding. Optical logic convention is high level of light emission for a binary ONE and low level of light emission for a binary ZERO. An optical path penalty not exceeding 1 dB to account for total degradations due to reflections, intersymbol interference, mode partition noise, and laser chirp should be tolerated by the receiver [14].

2.2.3. GPON Transmission Convergence (GTC) Layer

The GTC layer function is used for "Media Access Control" (MAC). Access of multiple users to a shared medium is controlled with this MAC. Distribution of the upstream PON capacity between the ONU's traffic using certain isolation and fairness criteria is referred to as "bandwidth assignment". Static bandwidth assignment is based exclusively on the provisioned parameters of the traffic contacts, while dynamic bandwidth assignment adds to it the activity status of the traffic-bearing entities and the bandwidth assignment occurs on timescale of the DBRu updates instead of the timescale of the individual service provisioning. Bandwidth allocation grants ONUs individual transmission opportunities within the timescale of a single GTC frame. GPON upstream access is done using pointers called "Transmission Container" (T-CONT). The upstream traffic is transferred in transmission containers which can carry identical traffic from one or many ports of the ONU [9]. T-CONT can be of five different types (T-CONT1 → T-CONT5) each with a different level of priority. Each T-CONT gives an ONU permission to send its data to the OLT during a given period. This technique supports also the categorization of data types in virtual queues. Depending on QoS factors and user requirements these different T-CONTs can be assigned to an ONU. Multiplexing and demultiplexing data streams are the responsibility of the "GPON Transmission Convergence" (GTC) framing layer. It also creates the frame headers and maintains internal routing. GPON specific datagrams are handled in the GTC layer which can be divided into two sub-layers, GTC framing sublayer and TC adaption sublayer. The Framing sublayer constructs GPON frames from data and extracts frames into individual data packages by communicating to a PLOAM client and the TC adaption sublayer. This layer provides an "ATM TC Client", "GPON Encapsulation Method" (GEM) TC adapter and "Dynamic Bandwidth Assignment" (DBA) control interface. GEM is independent of the type of the service node interface at the OLT as well as the types of UNI interfaces at the ONUs and provides a connection-oriented, variable-length framing mechanism for transport of data services over the passive optical network (PON). To simplify the functions and relations between the "GTC" Framing sublayer and TC Adaption sublayer the protocol stack can be divided into a "Control and Management plane" (C/M) and "User data plane" (U-plane). The C/M plane is responsible for the "Control and Management" of an ONU. Different parts of a frame are demultiplexed and processed at the GTC framing sublayer. OAM packages in the frame will be processed immediately as these packets are used for control information which is urgent. This data is located in the Frame header and can be bandwidth granting, key switching and dynamic bandwidth assignment. The PLOAM messages are forwarded to a PLOAM interface and not processed at this level. Those PLOAM messages contain management information which can't be transferred by OAM messages. Each ONU has an "ONU Management Control Interface" (OMCI), a separate control layer for ONU specific configuration. The C/M plane forwards this information to an OMCI interface used by other layers. The port ID-filter is used for multiplex purposes of data which have to be sent over GEM. ATM data is directed through the use of Virtual Path / Virtual Channel Identifier (VPI/VCI). At the U-plane user-data is forwarded to the ATM and GEM client. ATM data paths traffic is identified by the VPI. For GEM data a PORT-ID and PTI value is used. To filter incoming traffic the Alloc-ID values are used. These are unique numbers assigned by the OLT and attached to each data frame. Only frames with a valid Alloc-ID will be processed.

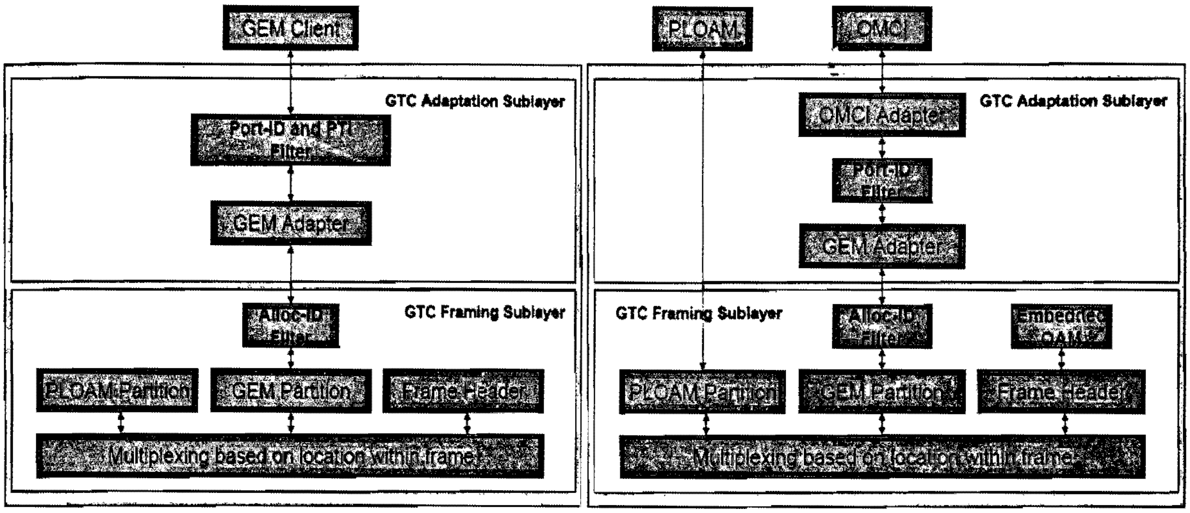


Figure 16: U and C/M plane

GPON is capable of running in three modes called ATM, GEM and Dual. The ATM mode has been rarely requested. The mode in which an OLT or ONU is running can be selected by the PON TC. ONUs and OLTs can communicate with each other while running in different modes as defined by the ITU-T, however not every combination is allowed. The allowed configurations are shown below [10].

		OLT		
		GEM	Dual	ATM
ONU	GEM	X	X	N/A
	Dual	X	X	X
	ATM	N/A	X	X

Table 5: GPON OLT and ONU modes

OLT assigns an 8-bit identifier to an ONU during activation using the PLOAM messaging channel. This ID is unique across the PON and remains valid until the ONU is powered off, deactivated by the OLT, or moves itself into an inactive state. Allocation identifier (Alloc-ID) is another 12-bit ID number that the OLT assigns an ONU to identify upstream traffic within that ONU. This traffic could be either a T-CONT or an upstream OMCI. Each ONU is assigned at least its default Alloc-ID, which is numerically equal to that ONU's ONU-ID, and may be assigned additional Alloc-IDs per the OLT's discretion [10].

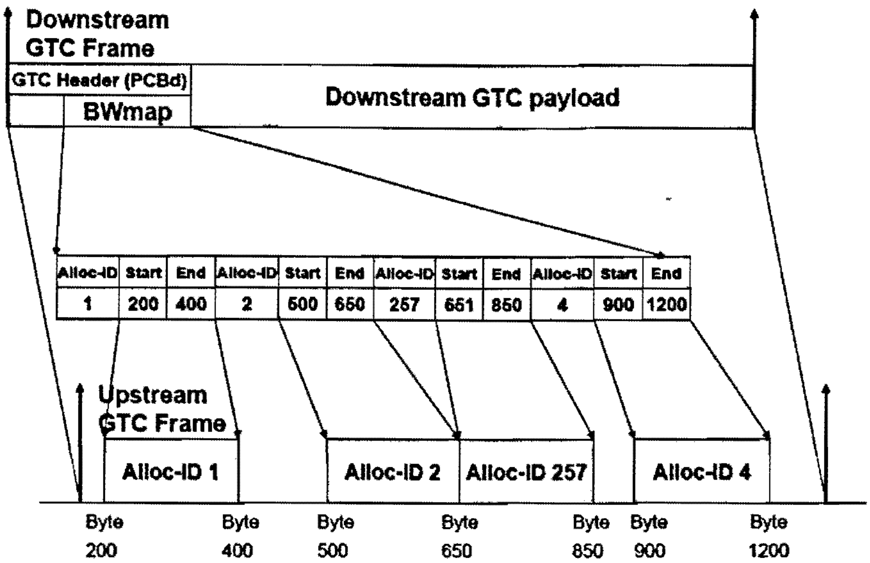


Figure 17: GTC media Access Control Concept

2.2.4. GPON Transmission Convergence (GTC) Downstream

The downstream direction traffic multiplexing functionality is centralized. The OLT multiplexes the GEM frames onto the transmission medium using GEM Port-ID which is a key to identify the GEM frames that belong to different downstream logical connections. Each ONU filters the downstream GEM frames based on their GEM Port-IDs and processes only the GEM frames that belong to that ONU and discard others.

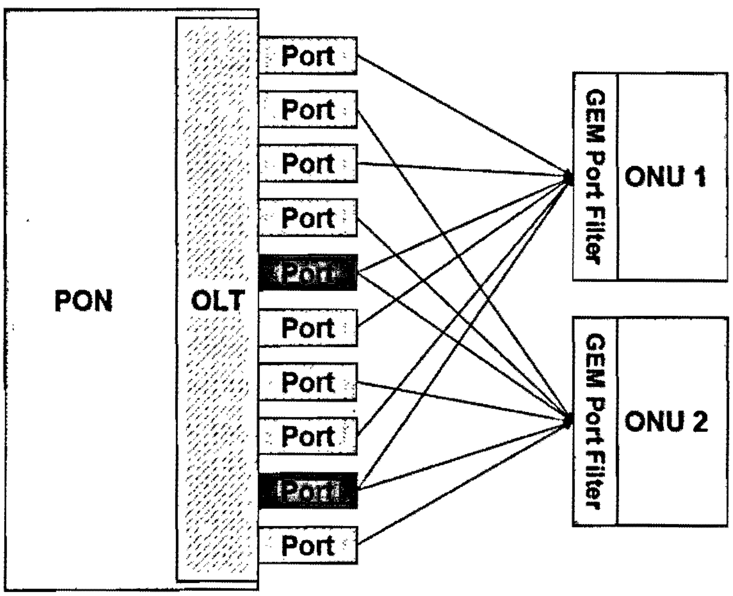


Figure 18: Downstream multiplexing (shaded GEM port indicates multicast)

The frame comprises of Physical channel message meant and used by all ONUs, and payload sections. In the payload section the GEM encapsulate data and TDM traffic. Within the GEM section is embedded the information of destination port of ONU. Each port as seen by PON has a unique identification and up to 4095, thus only the ONU, for which the traffic is destined, extracts the payload. For ATM cells which are directly mapped into the payload section, (VPI / VCI) are used for segregating the traffic at the ONUs. Downstream is broadcasted from the OLT to all ONUs in TDM manner. Every ONU must take into account only the frames intended for him what is assured by encryption. The downstream frame consists of the physical control block downstream (PCBd), the ATM partition and the GEM partition. The downstream frame provides the common time reference for the PON and provides the common control signaling for the upstream. The below figure shows that each frame is 125µs long, thus the amount of bytes that can be transferred by a single frame depends on the transfer speed [6].

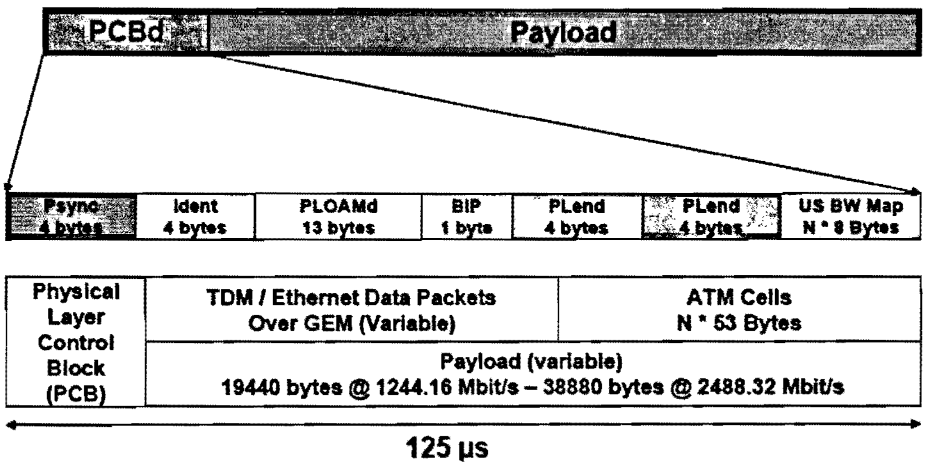


Figure 19: Downstream GPON frame (125µs frame)

The PCBd header contains several fields which are explained in detail in the ITU-T standard. These are the ***PSync*** (used by the ONU to synchronize on the incoming bitstream), ***Ident*** (MSB used to inform the ONU if the data is FEC encoded, second single bit not used and the remaining 30 bit is the "Super-frame Counter which keeps track of every transmitted frame and is increased each next frame, ***BIP*** (bit-interleaved parity of all bytes transmitted since the last BIP), ***PLOAMd*** (contains PLOAM messages), ***Plend*** (Payload Length downstream consists of two partitions. BWMap Length (Blen) field which gives an indication of the length of the bandwidth map and ATM Partition Length (Alen) which can allocate a maximum of 4095 ATM cells. ***US BW Map*** (Bandwidth map" (BWmap) contains the fields which describe the access slots for an ONU) [3].

2.2.5. GPON Transmission Convergence (GTC) Upstream

In the upstream direction, the traffic multiplexing functionality is distributed. The OLT grants upstream bandwidth allocations to each ONU on the PON network. These ONUs are identified by their allocation IDs (Alloc-IDs). The bandwidth allocations to different Alloc-IDs are multiplexed in time as specified by the OLT in the bandwidth maps transmitted downstream. Within each bandwidth allocation, the ONU uses the GEM Port-ID as a multiplexing key to identify the GEM frames that belong to different upstream logical connections. The Port-ID is 12 bit field and is part of the GEM header [10]

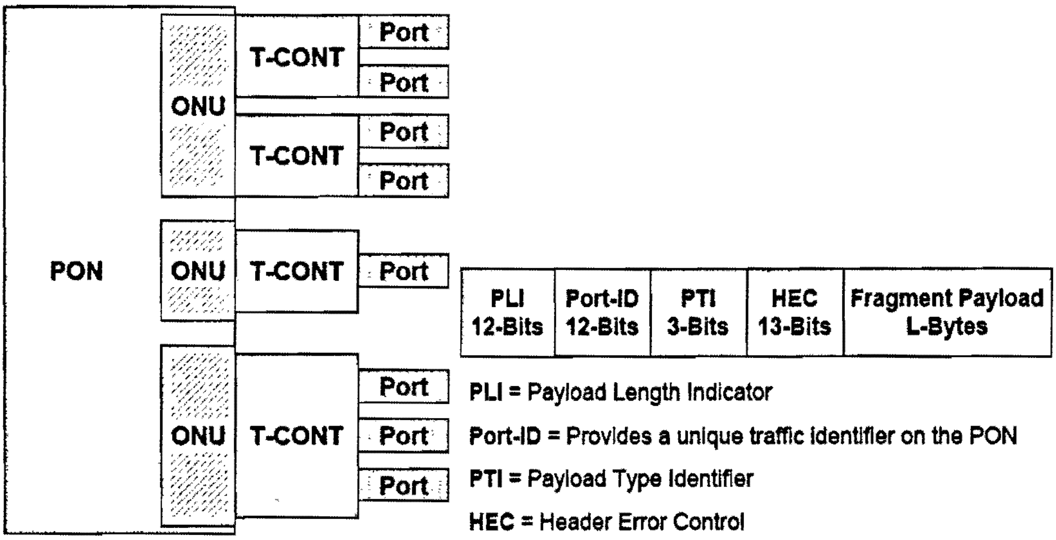


Figure 20: Upstream multiplexing and GEM header fields

G-PON operates in the burst mode in the upstream direction. The transmission bursts from different ONU transceivers require isolation and delineation at the OLT receiver. In upstream direction and based on the bandwidth requirement of each port, slots within the upstream frames are allocated to individual ONUs. The shared medium is made to behave as multiple point-to-point connections between an ONU and OLT by use of TDMA. The OLT, being the central point, is told about the bandwidth demand at each ONU. The upstream frame consists of multiple transmission bursts. A transmission burst is the interval during which the laser of an individual ONU transceiver remains turned on and is transmitting a pattern of zeros and ones into the optical fiber. Each upstream burst contains at a minimum the Physical Layer Overhead (PLOu). Besides the payload, it may also contain the PLOAMu (Physical Layer Operations, Administration and Management upstream), PLSu (Power Leveling Sequence upstream) and DBRu (Dynamic Bandwidth Report upstream) sections. The frame length is the same as in the downstream for all rates. Each frame contains a number of transmissions from one or more ONUs. The BWmap dictates the arrangement of these transmissions. During each allocation period according to the OLT control, the ONU can send from one to four types of PON overheads and user data [8], [10].

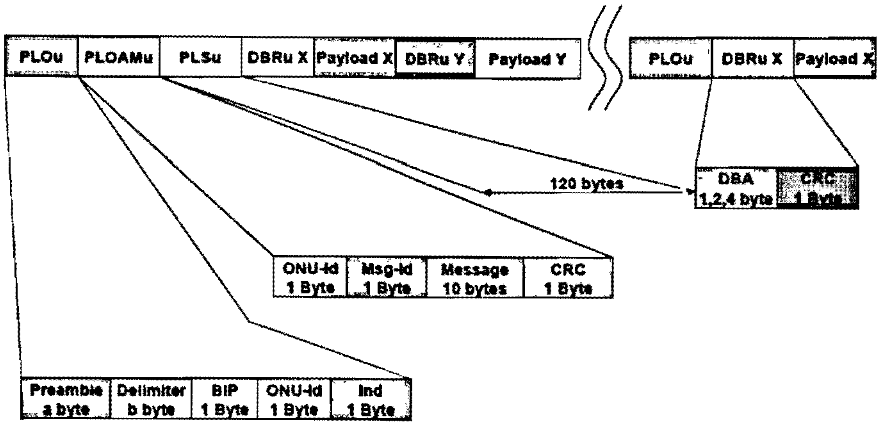


Figure 21: Upstream GPON frame Overhead

The PON overheads as shown in the above figure could be PLOu, PLOAMu, PLSu and DBRu. The figure below shows the payload which could be as mentioned earlier ATM cells, DBA reports or GEM fragments.

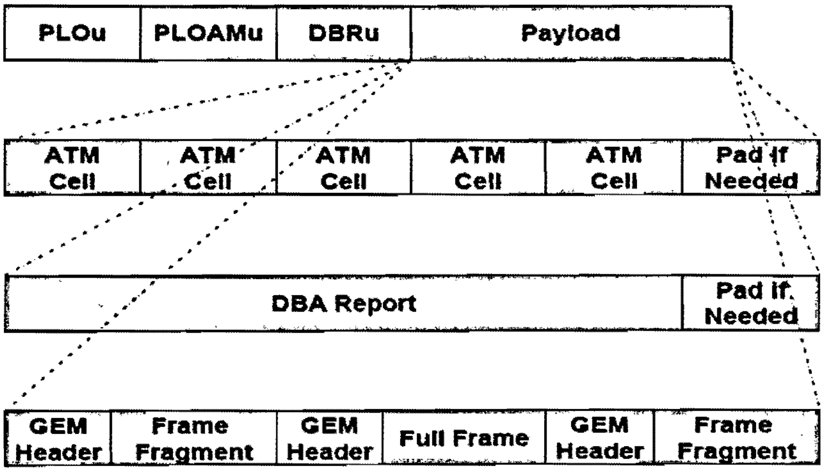


Figure 22: Upstream GPON frame Payload which can be ATM, GEM or DBA report

Chapter 3

3. EPON and GPON Comparison

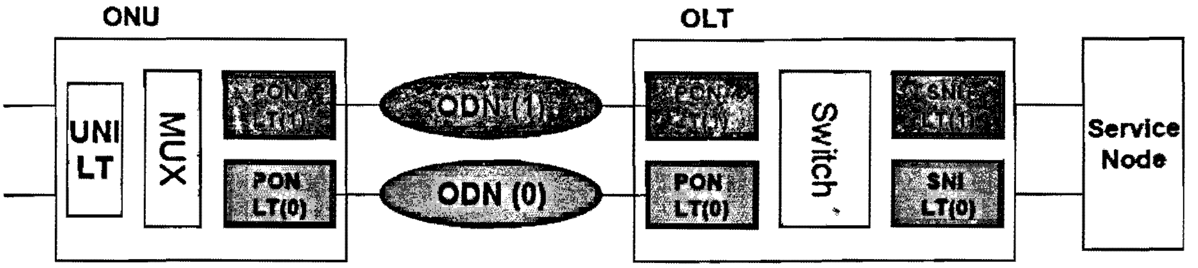
3.1. A Comparison between Standards

Network operators are currently deploying either EPON or GPON based on certain technology merits and region. These are but not limited to, Performance, Services, Cost efficiency, Convergence, Scalable, Flexible, Serviceable, Secure and many more. This paper compares most of the attributes that are of interest to network operators.

3.1.1. Network Redundancy

Fail safe PON's are one of the most important features that network operators are interested in when offering services to critical clients. This requires extending the basic model to include some mechanisms for backup and redundancy purposes. ITU-T includes some suggestions in its standards [1]. When a network is equipped with a backup system, there should be a procedure which decides when to switch between the "working system" and "protection system". Such procedure is called "protection switching" in the ITU-T standards. The decision when to switch is made upon two possibilities, "automatic switching" or "forced switching" similar to SDH.

Automatic switching is triggered in the worst case scenario when the system detects transmission problems, like loss of signal, a high "Bit Error Rate" (BER) or complete loss of frames. Forced switching is activated on request, for example temporary rerouting during maintenance of fibers or equipment. The ITU-T specifies these services for GPON as an optional functionality. The automatic or forced switching is triggered by the OAM messages. Depending of the risk level and cost systems integrators is free to use any of the suggested redundant schemes in the standard or use their own schemes. The most expensive and reliable model is the duplicate use of every system component as shown in the below figure.



POL LT = PON Line Terminal; UNI LT = User Node Interface Line Terminal; SNI LT = Service Node Interface Line Terminal

Figure 23: PON Full Duplex System

There will be basically two N:2 splitters in the field feeding the ONU from two different paths. However ITU-T offered some less expensive solutions where only some components are duplicated. Figure 24 shows a system where the fiber is duplicated. Figure 25 shows a system where the OLT and fiber are both duplicated. The IEEE doesn't specify these backup solutions for their EPON networks. However, as EPON is a PON based network as well, the solutions defined by the ITU-T should be usable as well [1].

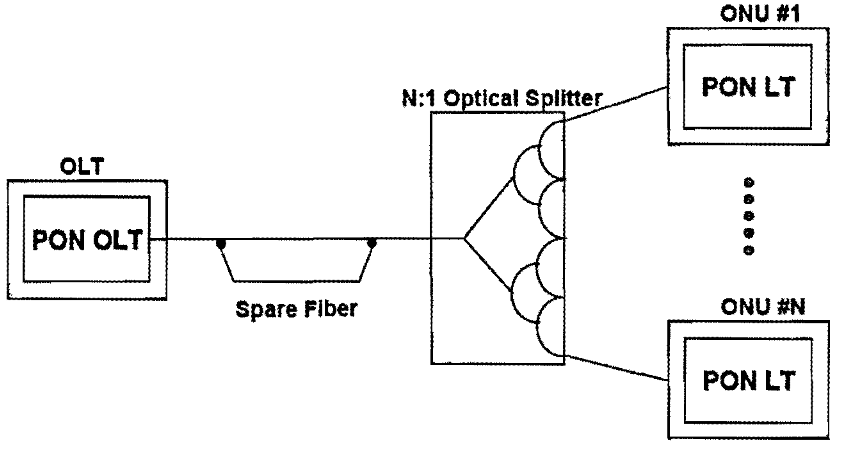


Figure 24: PON Fiber Duplex System

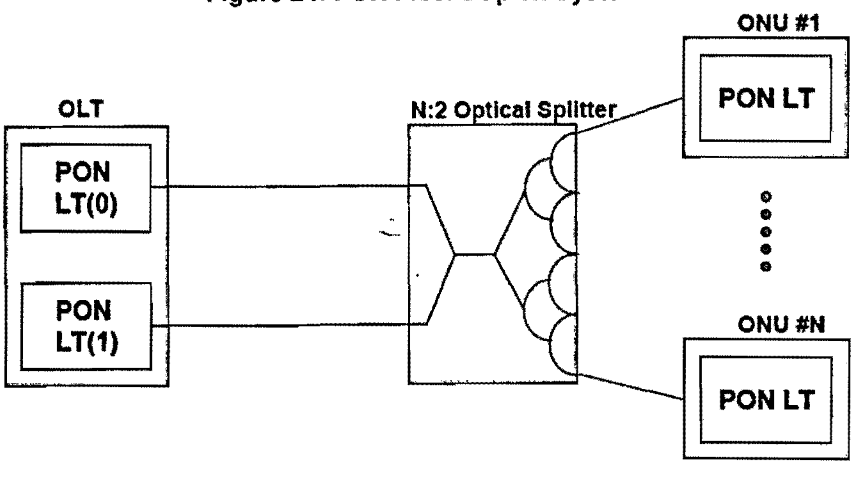


Figure 25: PON OLT Duplex System

As per the standard the protection switching function should be optional including both automatic protection switching and forced switching. All the configuration and switching mechanism should be possible, even though they are optional functions [1].

3.1.2. Broadcast Services Overlay

An advantage of the P2MP topology of a PON network is its broadcast function in nature. This function can be used to send broadcast services to the end user such as television and video on demand. In the future more services can be added. All additional services use the enhancement band and are transmitted on a separate wavelength. WDM is used to add additional wavelength to a fiber and extract or drop this wavelength at the user side as shown below.

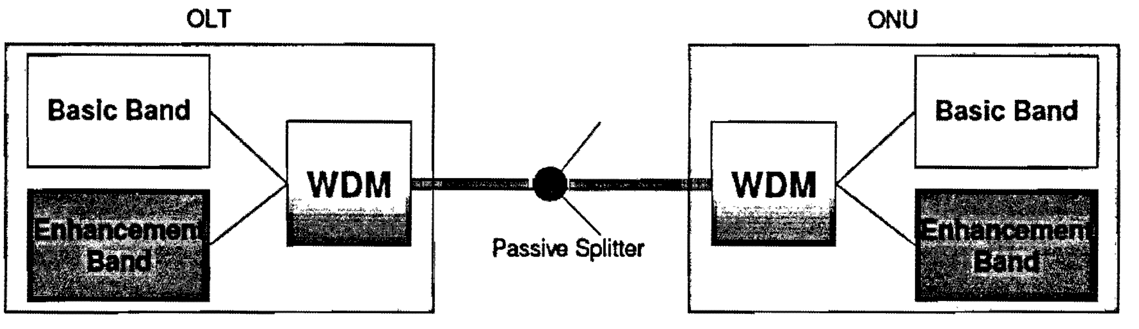


Figure 26: Enhancement System

GPON systems implement such Enhancement-band with WDM technique as long as the wavelengths don't conflict with the GPON band-scheme. The IEEE doesn't mention any implementations for additional services in their EPON networks although similar technique as in GPON networks could be applied to EPON networks.

3.1.3. Multiple Standards on a Single Fiber

It is not possible to use GPON and EPON on the same fiber. EPON systems upstream and downstream wavelengths conflicts with GPON systems. The upstream wavelength of 1310 nm and downstream of 1490 nm for EPON lies within the band-plan for GPON and hence EPON traffic will corrupt GPON traffic and vice versa. As a result network operators need to decide which standard to use in their implementation and this paper will help in this regard. Neither standard, ITU-T and IEEE, mentions anything about coexistence between the two standards, but network designers are free to implement additional fibers or lambda-converters to over come the above problem. The lambda-converters will create a logical P2P link and segments from GPON or EPON can then be connected to a network gateway. This gateway will have GPON network on one side and EPON network on the other side. This solution is not an efficient solution as it suffers from delay since data will be extracted from one frame and put into the other. Besides it will be very difficult to manage and administer this network for QoS as each segment will have it own management rules based on its protocol.

3.1.4. Physical Layer Overhead

Electrical components built into the physical layer of an ONU and OLT need time to stabilize, switch on and switch off, in particular the transmitters or lasers. After the laser stabilizes the receiver needs time to synchronize before the data can be transmitted. All those processes are part of the physical layer and therefore often referred as "Physical Layer Overhead" (PLO). The efficiency of a system and costs to produce it depends partly on the specifications of these PLO parameters. Transceivers with tight timing constraints are more expensive to produce. Each standard defines certain required parameters. GPON on/off is almost 13ns while EPON is 512ns and hence GPON is more efficient. At the same time since GPON transceivers has tight timing they are more expensive to produce than EPON transceivers [14].

3.1.5. GPON and EPON Reliability and Security

In any network reliability and security are important issues. Security is needed to guarantee privacy protection of user data and to prevent other users from masquerading as another ONU/ONT or user and finally it should allow cost-effective implementation. Reliability is needed to ensure error free data transmission and prevent damage due to hardware failure. P2MP network structure of PON poses privacy protection of user data concerns where data transmitted from the OLT can be seen by all connected ONUs. Downstream protection is required while upstream protection can be additional since the risks of tapping physically into the fiber are very small. For error free reliable transmission, both upstream and downstream data have to be protected. Since the network in between the OLT and ONU is passive, hence these protections schemes are implemented at the user side. These schemes add certain extra information to the data packages that are used by the OLT and ONU to verify the integrity of the received data. GPON further tries to take care of threats like reprogramming the ONU in such way it can listen to all downstream data. GPON implements reliability through the use of CRC algorithm to protect the header. For GEM frames a HEC or CRC value is used to protect the header. GPON supports "Forward Error Correction" (FEC) code for data transmission. This result in increased link quality, higher bit rates, longer reach distance and more split ratios. The system uses Reed-Solomon (RS-255,239) for FEC encoding. The 16-bytes parity is extra overhead which results in less user data that can be sent on the frame. All GPON downstream bits are FEC coded while GPON upstream frames excludes the Delimiter and Preamble from the FEC encoding, the BIP field will be the first section of the coding. GPON downstream data is scrambled using the "frame-synchronous scrambling polynomial". All bits are scrambled except for the first Psync bits in the PCBd header. GPON uses "Advanced Encryption Standard" (AES-128) to encrypt downstream data and protect against third party threats. AES encrypts

128 bits of data blocks which requires a key of 128, 196 or 256 bits long. GPON supports "Counter" (CTR) AES mode. This method requires a key and counter for encryption purposes as shown in the below figure. This key is introduced the first time by the OLT to the ONU during initialization process and then updated by "key-request-message" using the PLOAM message from the OLT. The ONU will generate a new key and send it back to the OLT in response to this message. No specific method is defined to secure GPON upstream data. If security is required it should be implemented at a higher level.

No encryption is defined by IEEE for EPON and should to be implemented at higher levels if needed. For reliability every transmitted frame is tagged with a "Frame Check Sequence" FCS to detect transmission errors. This FCS is a 32-bit "Cyclic Redundancy Check" CRC value. With this CRC value correction of transmission errors isn't possible. When an incorrect CRC is detected the whole frame will be discarded. To reduce transmission errors data needs to be constructed in such a way that there are enough ZERO's and ONE's for synchronization and for this purpose EPON applies 8B/10B encoding. Another purpose of 8B/10B encoding is maintaining the DC level [1], [9].

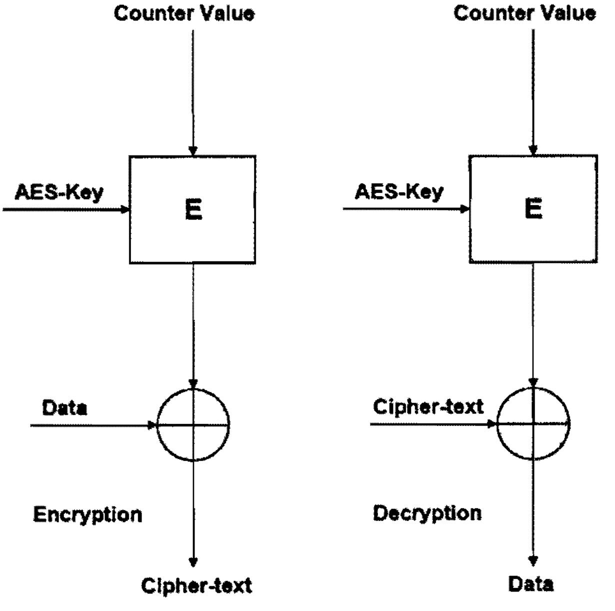


Figure 27: AES CTR mode

3.1.6. EPON and GPON Performance

PON efficiency depends on the amount of users and protocol efficiency. In P2MP system the available bandwidth at the main fiber is split from the OLT to the entire ONUs. Hence the bandwidth usage is managed by the OLT and ONU level. An ONU won't use the bandwidth if it does not receive grants from the OLT. The OLT is the control station and divide the available bandwidth amongst the users. Another efficiency factor is the in a PON network is the overhead needed to transmit data. How much of the transmitted data is a payload and how much is header. For downstream and upstream data transmission extra management and control packets are inserted. Depending on the particular protocol requirements these packets could consume more or less than other protocols [22]. For GPON downstream frame at 125 μs for 2.48832 Gb/s is 38880 bytes long. Part of this frame is payload and the other part is header. Header is made of 30 bytes + the "US BW Map" field which is N * 8 bytes, where N is the amount of bandwidth reports for the ONU. This implies that the header is dynamic and hence the bandwidth can be variable. The effective downstream GPON bandwidth efficiency is 92% which can be divided by a maximum of 64 users with support to 128 users in the future. On the other hand, EPON downstream bandwidth efficiency is almost 75% with the maximum amount of users limited to 32 [22].

3.2. EPON and GPON Quantitative Comparison

The below figure is an overview of the different protocols and services supported by GPON and EPON. As it can be seen EPON has less complication and is built on an Ethernet frame and the service it supports are those supported by the industry standard "Internet Protocol". GPON supports more standards and services and is built on GEM frames. Thus translation from GEM to Ethernet is required when IP services are required.

<table>
<tr><th colspan="4">IEEE EPON</th></tr>
<tr><td rowspan="3">RF Video</td><td>Internet</td><td>IPTV</td><td>VoIP</td></tr>
<tr><td colspan="3">IP</td></tr>
<tr><td colspan="3">Ethernet</td></tr>
</table>

Table 6: EPON protocol/services

<table>
<tr><th colspan="4">ITU-T G-PON</th></tr>
<tr><td rowspan="5">RF Video</td><td>Internet/IPTV/VoIP</td><td rowspan="2">POTS (64k) / T1 / E1</td><td rowspan="3">Voice over ATM</td></tr>
<tr><td>IP</td></tr>
<tr><td>Ethernet</td><td>TDM</td></tr>
<tr><td colspan="2">GEM</td><td>ATM</td></tr>
<tr><td colspan="3">GTC (125 Micro Sec Frame)</td></tr>
</table>

Table 7: GPON protocol/services

3.2.1. Comparison Table between EPON and GPON Standard

	GPON	EPON
Downstream Bandwidth	2.488 Gbps	1.250 Gbps
Upstream Bandwidth	1.250 Gbps	1.250 Gbps
MAC Layer Protocol Flexibility	Flexible GPON Encapsulation Method (GEM) & ATM	802.3 Ethernet Only
Protocol Efficiency	High (>90%)	Low – 8b/10b Encoding
Optical Reach and split ratio	20 km (max 60) with 32:1 split 1:64 (1:128 planned)	10 km with 32:1 split (max 20Km)
Multicast Support	Native Support	Native Support
Standards Control	FSAN / Operators (ITU-T G.984) series	IEEE (802.3ah)
Dedicated rates (32 split)	75/35 Mbps	30/25 Mbps
Data transport	ATM or Packet	Packet (variable)
Encryption	AES-128/G & CTR supported Galois Mode (G) Counter Mode (CTR)	AES-128/CTR mode Counter Mode (Not mentioned in the standard but could be implemented at higher levels)
Deployment Maturity	Evolving	Mature
Payload / Transmission	Ethernet, TDM, ATM	Ethernet
Investment Cost	More up front investment	Cheaper to deploy
Transmission coding	Scrambled NRZ	8B10B
Splitting ratio	16/32/64/128	More than 16
Span loss	20 dB (Class A) 25 dB (Class B) 28 dB (Class B+) 30 dB (Class C)	20 dB (PX10) 25 dB (PX20)
Standards Bodies Mission/Objective	Full Service Access Network (FSAN) 1st Draft 2002	Ethernet in the First Mile (EFM) 1st Draft 2000
Attendees	Service Provider focused	Enterprise and consumer market focused
Committee Operating Protocol	Carriers drive and approve vendors technical recommendations	One person- One vote
Wavelengths	Specified	Specified

	GPON	EPON
Bandwidth efficiency (Downstream)	Greater than 90% ~92% as a result of: NRZ scrambling (no encoding) Overhead (8%)	Less than 75% ~72% as a result of: 8B/10B encoding (20%) Overhead & Preamble (8%)
QoS Quality of Service	Specified	Left to vendor
Network synchronization	Specified	Left to vendor
Security	Specified. AES is part of the standard	Left to vendor. AES used by various vendors.
Laser on/off	≈13 ns	512 ns
AGC (Auto. Gain Control)	44 ns	≤400 ns
CDR (Clock Data Recovery)	44 ns	≤400 ns
3rd Wave Length for CATV overlay	Standardized	Not Standardized
Fiber protection	Standardized	None
Downstream security	AES (Advanced Encryption Standard)	None
FEC (Forward Error Correction)	Standardized	Standardized
TDM Support/transport	Native via GEM or Circuit Emulation over Ethernet.	Circuit Emulation over Ethernet
ONU/ONT	DFB/PIN(APD)	FP(DFB)/PIN
OLT	DFB/APD	DFB/APD
Wavelength Band Plan	1490 nm down 1310 nm up 1550 nm video overlay	1490 nm down 1310 nm up 1550 nm video overlay
Revenue BW	2300 Mbps	900 Mbps
OAM & P	OMCI is mandatory. Full FCAPS on ONT and services.	OAM is optional and minimally supports: failure indication, loop-back and link monitoring to the ONT. Provisioning and services are out of scope.
Network Protection	Optional 50ms switching time	None specified
Interoperability	FSAN and ITU-T	None specified
Branches	Max.254	Max. over 16

Table 8: GPON vs. EPON Comparison

* The above table is based on information provided in both standards (IEEE 802.3ah and ITU-T G.984.1,2,3,4, & 5)

3.2.2. EPON and GPON Comparison Figures

Much of the cost of PON deployment is in the infrastructure. Huge investment has been made in OSP, so when talking about the Next generation PON we should be reusing the installed infrastructure.

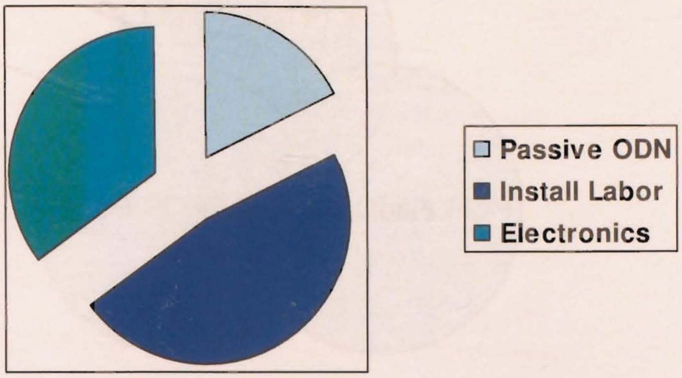


Figure 28: GPON and EPON PON Deployment cost

The below figure shows the interoperability level of both standards with the offered services. GPON offers interoperability up to the data link layer while EPON and since it is Ethernet based can extend its interoperability to the Ethernet services through provisioning, service flows and traffic management.

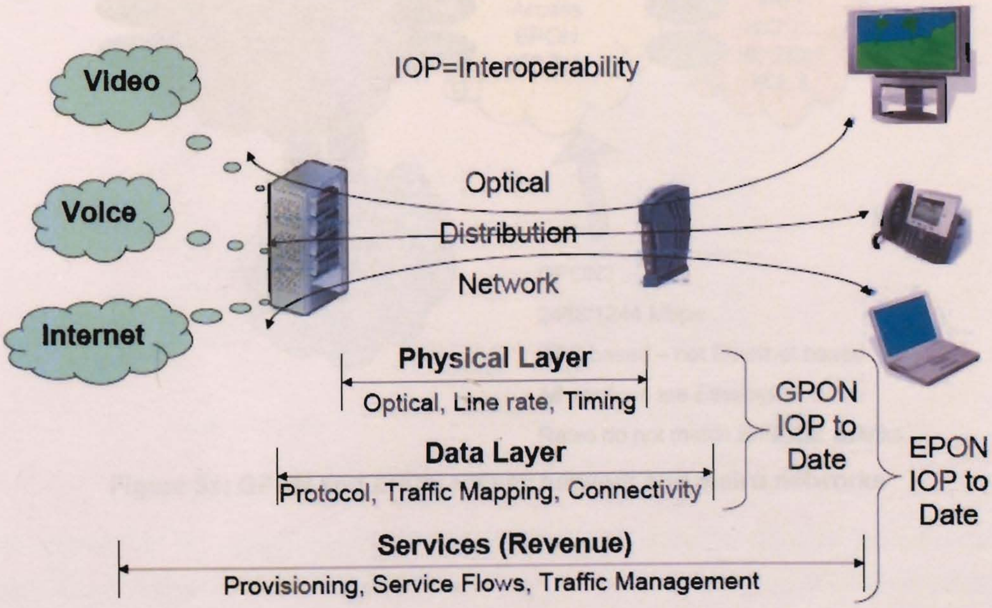


Figure 29: GPON and EPON Interoperability Comparison

When considering evolution paths for EPON and GPON; WDM-PON, 10G-PON and long reach PON are being researched. Lots of challenges face any of these paths, but according to market specialists WDM-PON seems to offers the easiest evolution path and future proof for any bandwidth increase.

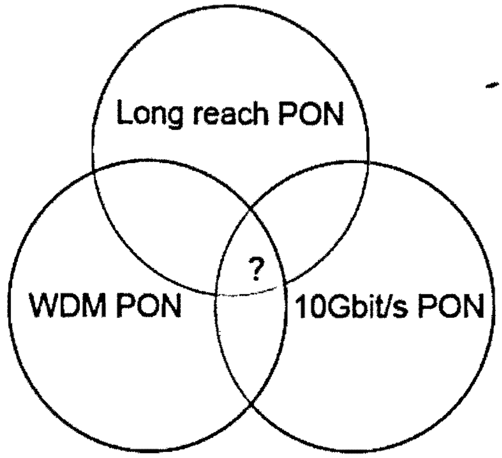


Figure 30: GPON and EPON NG requirements Comparison

EPON offers an extension of the metro networks which is already deploying Ethernet based networks, while GPON has extra encapsulation methods to accommodate Ethernet as well as different rates that do not match E/FE/GE uplinks.

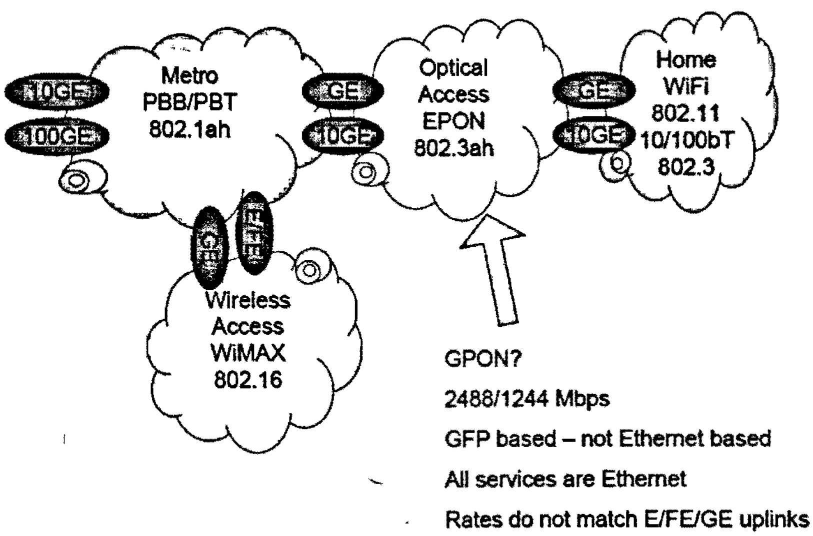


Figure 31: GPON and EPON access network and metro networks

EPON offers direct mapping of Ethernet frames into EPON frames thus reducing the processing times and presents IP services to the user with less conversion.

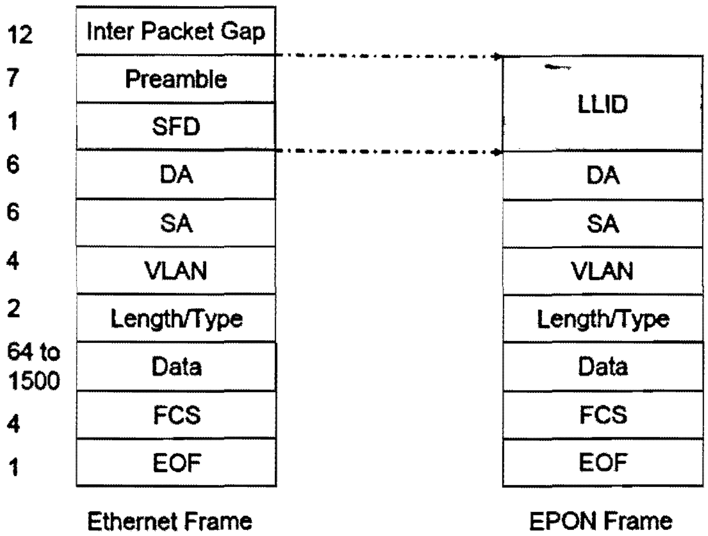


Figure 32: EPON frame straight forward mapping to Ethernet frame

GPON encapsulates Ethernet frame using GPON Encapsulation Method (GEM) and adds to it the GEM header and hence GPON frame is not Ethernet frame.

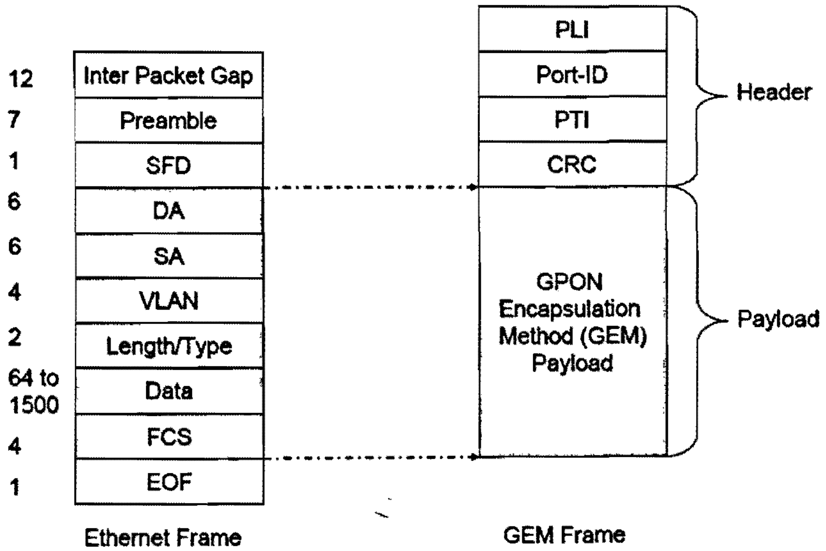


Figure 33: GPON frame ≠ Ethernet frame

The P2MP topology of both standards (EPON and GPON) best suits the video broadcast service in the downstream direction due to its efficient use of bandwidth. The below figure is just an example to illustrate such advantage where the bandwidth increase only in the case were users choose to watch different channels.

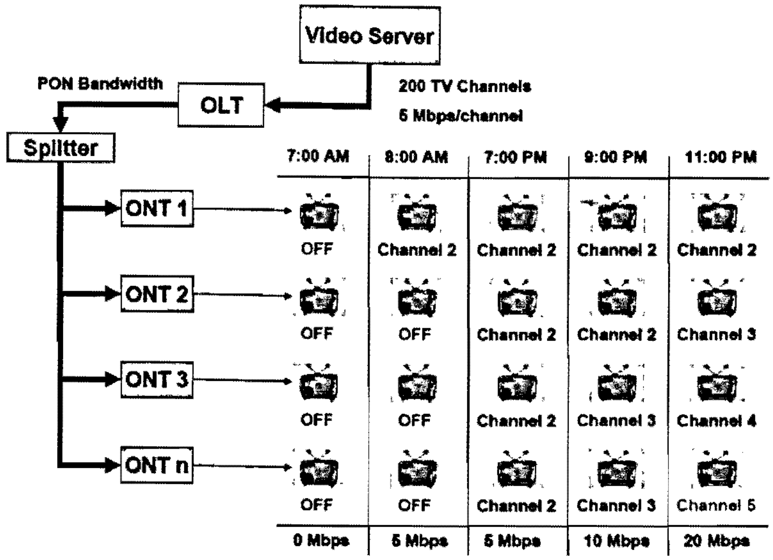


Figure 34: GPON and EPON Broadcast TV Bandwidth Optimization over PON

The below figure shows the available bandwidth for users at different split ratios. This figure is calculated based on the following formula: Bit rate per ONU = EPON (1.2Gbps/n) or GPON (2.4Gbps/n) where n is the number of ONU's. Thus for the same number of users GPON offers higher bandwidth than EPON.

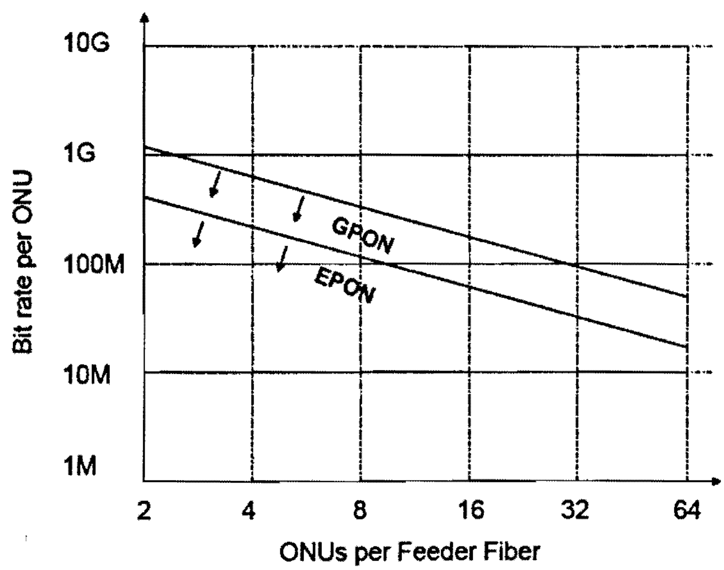


Figure 35: GPON and EPON Low Cost PON Comparison

EPON is managed like any other Ethernet switch via SNMP through IETF MIBs. Additional control messages are Multi-Point Control Protocol (MPCP) GATEs/REPORTs for BW granting, as well as EFM OAM messages. MPCP and EFM OAM frames are multiplexed with regular Ethernet traffic. In GPON there are three different types of control messages: OMCI, OAM, and PLOAM. Their roles are shown in the table below. In either case, REPORTs are transported upstream as payload traffic.

Control Function	EPON	GPON
Provisioning of ONT service defining layers above L2	IETF MIB / SNMP	OMCI (Ethernet or ATM)
BW granting, Encryption key switching, and DBA	MPCP (higher layer for encryption key)	Embedded OAM (Header overhead)
Auto discovery, and all other PMD and GTC mgt info.	MPCP and EFM OAM	PLOAM (ATM)

Table 9: GPON and EPON Control Messages Comparison

Dynamic Bandwidth Allocation (DBA) allows a system to assign upstream timeslots in real-time, based on the instantaneous demand of a given ONT, and hence uses the upstream bandwidth more efficiently. Elements of GPON and EPON DBA schemes are outlined in the table below.

	GPON DBA	EPON DBA
Granting Unit	GTC Overhead	MPCP GATE frame
Control Unit	T-CONT	LLID
Identification of Control Unit	Alloc_ID	LLID
Reporting Unit	ATM: ATM Cell/GEM fixed length block	MPCP REPORT frame
Reporting Mechanism	Embedded OAM	Separate REPORT frame
Negotiating Procedure	GPON OMCI	N/A

Table 10: GPON and EPON DBA Elements Comparison

In EPON, Ethernet frames are carried in their native format on the PON. This simplifies the layering model and the associated management. Services are all mapped over Ethernet (directly or via IP).

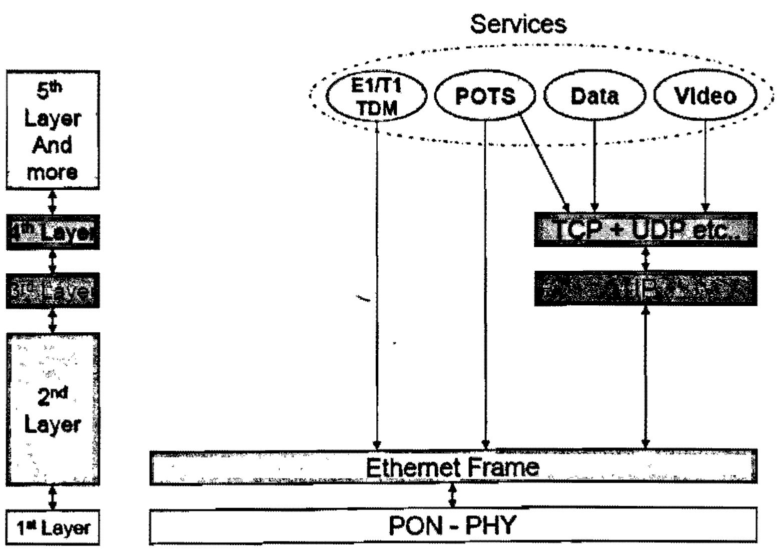


Figure 36: EPON Service Accommodation Method (Layering Method)

In order to accomplish the same in GPON, two layers of encapsulation are required. First, TDM and Ethernet frames are wrapped into GTC Encapsulation Method (GEM) frames. Secondly, ATM and GEM frames are both encapsulated into GTC frames that are finally transported over the PON. See the figure below.

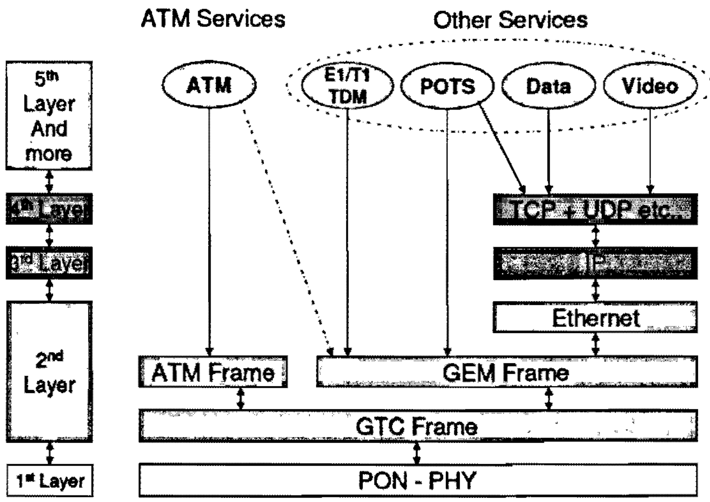


Figure 37: GPON Service Accommodation Method (Layering Method)

Chapter 4

4. EPON and GPON Implementations and Recommendations

The end user does not need to be overloaded with technical details and hence services should be provided in a plug and play manner. These services are television, internet and telephone, the so called "Triple Play" services. An advantage of optical networks can be a high bandwidth and less interference. An electrical interface at the end user is constructed using industry standard interfaces and these are RJ-45 for internet, RJ-11 for telephony and coax / HDMI for television. Each interface is driven by an electrical circuit which requires a certain format or protocol for transportation. It is preferred to have a format supported by PON network or else data conversion from one protocol to another is required. For Internet service, Ethernet protocol can be used. Almost every PC is equipped with an Ethernet interface; moreover, additional off the shelf network equipment is available for home usage. For a telephony service, digital audio can be encapsulated into two protocols. These are "Voice over IP" (VoIP) and "Voice over ATM" (VoATM) standardized in ITU-T H.323 and ITU-T I.363.2 respectively. Television service can be implemented using the Enhancement band as discussed that provides the television in a broadcast way like the current CATV system. At the ONU this signal can be converted to an RF signal or digital signal which can be sent to the television. As shown in figure 37, a PON signal requires more processing by GPON stack. Moreover, GPON provides two interfaces, GEM and ATM. ATM interface could be used to transport telephony service which could be realized through the use of VoATM to convert from ATM channel to RJ-11 interface. GEM interface could be used to transport internet service. This requires conversion from Ethernet to GEM which is standardized and can be presented as an Ethernet interface to the user. EPON could be implemented in a similar manner as GPON. Except that the Enhancement band is not specified for EPON although it can be implemented same as in GPON. At the ONU level EPON provides an Ethernet interface which can be used directly as a user interface without any conversion. In fact this is one of the major differences between EPON and GPON. For telephony, VoIP protocol could be used since the IP is the available interface and since it is easier to encapsulate VoIP into Ethernet than encapsulating VoATM into Ethernet. Finally, television service is realized in the same way as in GPON through the use of an extra wavelength. A complete overview is shown in figure 38 of both configurations.

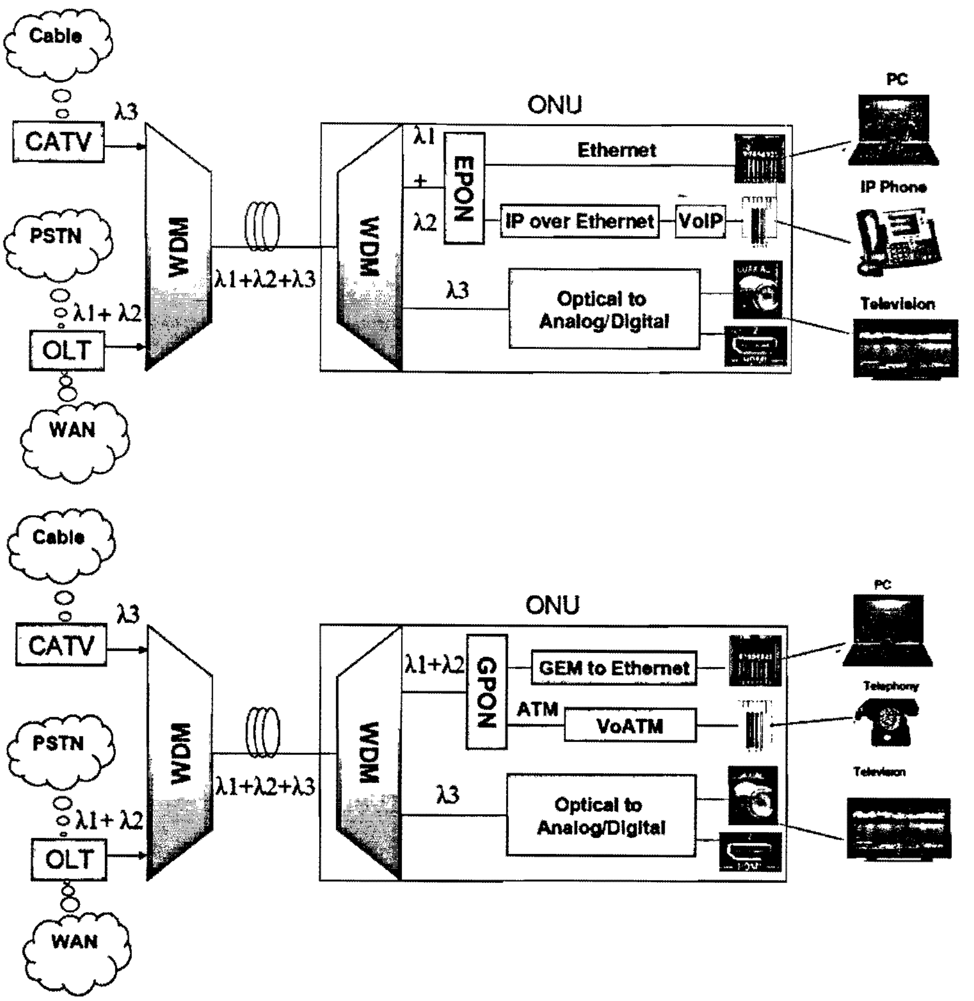


Figure 38: GPON and EPON Implementation Examples

The purpose of most new project implementation is to provide a high speed, multiple services access point to the end-user. Several techniques are available and PON is one of them. Based on Telco-companies strategic planning, ease of implementation, good ROI initiatives, region, and sometime trend these companies will deem if PON network structure is suitable or not. Due to the broadcast nature (P2MP) and possible P2P configurations, PON networks looks attractive. The previous sections discussed two most advertised and implemented standards, the EPON and GPON, which provide implementation options in PON. Although the standards discussed show networks with a standardized design, these networks can be modified by system designers to meet the user requirements. However, if any modifications are made, they should not conflict with the standardized parameters.

Sometimes project requirements may not be fulfilled by a single standard. GPON standard is intended to fulfill most of the current user and small business services. But if a single standard fails to fulfill all project requirements, then certain parts of the standard can be used and other parts need to be filled in by other standards or maybe a complete new standard. A disadvantage of not using the complete standard for the implementation may be the incompatibility and interoperability with existing equipment.

It will be simpler for "third parties" to design their hardware for a network designed according to a standard. Networks which are partially designed by standards and partially by user implementations require specifically designed hardware to conform with the customers specifications and thus would cost more and require more time to produce. Hence it is always recommended to use industry standards as most of the manufacturers will follow the standard in their hardware manufacturing. And the user will benefit from competition and mass production.

The big question is "Which standard to implement". One of the purposes of this project is to help find an answer to this question as there is no straight forward answer. To decide to use EPON or GPON in new project implementation several aspects needs to be taken into consideration. The battle between EPON and GPON continues to strengthen as both of the standard bodies jumped into standardizing the next generation technology to proof to network operators that their standard provides an upgrading paths for the capacity of current Passive Optical Networks (PON) used for the Fibre-to-the-Home deployment.

The current GPON and EPON architecture are based on TDM-PON access technique to share the media. In order to achieve higher bandwidth (10 Gbps), some techniques to increase the power budget and increase receiver sensitivity are necessary. Some of these techniques are the use of APD, forward error correction (FEC) and optical amplifiers. Semiconductor Optical Amplifier (SOA) is more favorable to use because of its feature of providing high gain and operating possibility at 1310nm and 1550 nm wavelength region. Future directions will be discussed in the forthcoming chapters.

4.1. Implementation Considerations

This section discusses some considerations to help decide which standard to use EPON or GPON in a new design. The previous sections highlighted main characteristics of each standard and their possible configurations. When designing a new network in a certain neighborhood, a good design would preserve low costs while keeping the efficiency as high as possible. A neighborhood would require several OLT's depending on the amount of bandwidth required by each user and the number of users. GPON supports 64 and even 128 in the future, where EPON currently supports 32 users.

For EPON the effective rate will be 31.25 Mb/s if the available bandwidth at the OLT has to be divided amongst the maximum possible connected ONUs or users. Two possible upgrade options exists for EPON, one is one is increasing the available bandwidth and the second option is allowing more users to be connected simultaneously. Currently the available bandwidth for each of the 32 users is more than enough to serve an average household using telephone and internet. Note that the TV distribution is not using this bandwidth since it has its own separate wavelength "outside" the actual PON system.

For GPON the effective network bandwidth will be (2488.32 / 64) 38.88 Mb/s for 64 users or 19.44 Mb/s for 128 users. A GPON network is also scalable and higher transmission speeds have already been tested by many manufacturers and more users per ONU should be possible. The worst case bandwidth of 19.44 Mb/s is currently more than enough for an average user keeping in mind that with higher transmission speeds coming up this bandwidth could be increased in the future. Like EPON, the Television signal isn't included in this bandwidth.

There are several equipment manufacturers who already produced or proved in a lab test that equipment with higher specifications are already available but not yet officially certified by IEEE or ITU-T. The available bandwidth and users that can be connected now shouldn't be the deciding factor. But if a choice has to be made upon this issue GPON would be preferable due to its higher bandwidth and more users per OLT.

Another deciding factor might be the number and way services are mapped to the PON network. For telephony this could be done using two standards, VoATM and VoIP. For EPON this is a mapping to VoIP while GPON it is VoATM. Each protocol has its own advantages and disadvantages but VoIP seems to be more popular now. The increased popularity of VoIP for being able to use the standard Ethernet protocol, VoATM on the other hand is a more specific technology but more reliable and uses less overhead. Another advantage of VoIP besides being a commonly used technology is the flexibility where a user can register with his or her account at a "Session Initiation Protocol" (SIP) sever and start making VoIP calls. Any internet connection could be used for this purpose even on a mobile or fixed phone. For VoATM it is more complicated as the network structure needs to be designed according to specific requirements to establish a connection. EPON provides support for both services without too many conversions while GPON can use VoIP but needs the extra conversion to GEM frames. Due to the popularity and maturity of the Internet and Ethernet protocol, many services used via the Internet could be implemented at the ONU when their development is at an acceptable level. Since EPON provides the smoothest transition possibilities, this migration from the Internet to ONU seems to be achievable. For internet EPON provides the simplest interface without any conversion while for GPON networks conversion from GEM frames to Ethernet is required. Thus if a choice has to be made upon Ethernet compatibility EPON would be preferable due to its interoperability, simplicity and flexibility with Ethernet protocol. Finally EPON devices are cheaper to manufacture due to the relaxed timing specifications mentioned previously. GPON devices have smaller timing for circuits to operate and hence more expensive in their manufacturing. So the cost of implementing the same number of users will be higher in GPON than in EPON.

4.2. Integration, Test and Management of PON CPE

Customer premise equipment (CPE) management and support is part of the new service establishment. Some of the CPE functions include:

1. ONU/ONT
2. Battery Backup Unit
3. Router (Data)
4. ATA (Voice)
5. Set Top Box

Some trends of the broadband CPE market

Phase 1: Access Infrastructure Provider (AIP) supplies, installs and maintains CPE. Usually CPE vendor is the network equipment vendor.

Phase 2: AIP may then offer limited range of CPE (all thoroughly pre-tested). Over time this approved range grows. Content Providers may have the option to have their CPE approved. Self install options may be developed.

Phase 3: As interoperability, standards and self-install practices mature the AIP can move to a full retail model. CPE is 'off-the shelf".

GPON and EPON are probably at Phase 1. They can make it to a retail model with a lot of work through both industries standards bodies. Instead of 5 boxes, G/EPON CPE vision aim for two, with three being an intermediate step.

Intermediate plan:

1. Box 1 = ONT and Batter Backup.
2. Box 2 = Router and ATA.
3. Box 3 = STB

Benefits of such vision are:

1. Reduce Complexity.
2. Easier Install.
3. Reduce Power Consumption.
4. Reduced Cost.

The ITU-T standard specified some physical layer parameter measurements that are required to provide the GPON system with a basic layer supervision capability [14].

Transceiver parameters monitoring:

1) Normal State Status.
2) Degradation detection: find the potential fault before they become service-affecting, and identify the source of the problem (OLT,ODN,ONT).
3) Fault management: Detect, localize and diagnose faults.

In order to achieve these objectives, the following performance items should be monitored in a PON:

- Transceiver temperature (OLT and ONT – typical values: -45 to 90 °C)
- Transceiver voltage (OLT and ONT – typical values: 0 to 6.55V)
- Laser bias current (OLT and ONT – typical values: 0 to 131mA)
- OLT transmit power (typical values: -10 to 8 dBm)
- OLT receive power (typical values: -34 to -8 dBm)
- ONT transmit power (typical values: -10 to 8 dBm)
- ONT receive power (typical values: -34 to -8 dBm)

4.3. FTTH Cables

There are 4 types of cable according to the different locations of the optical cable in the FTTH network architecture, namely the feeder cable, distribution cable, drop cable and indoor cable [28].

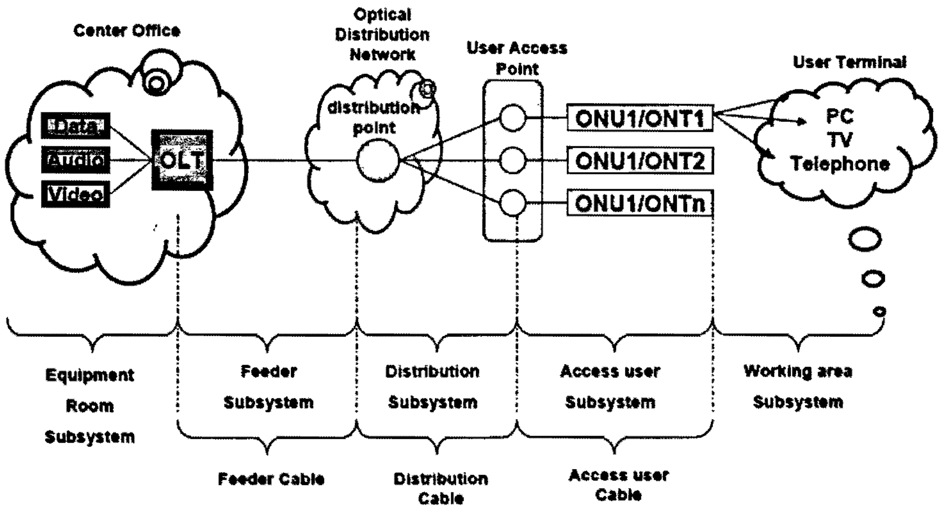


Figure 39: Structure model of FTTH system

4.3.1. Feeder Cable

Feeder cables are connected between the central office (OLT) and the distribution point. In general, feeder cable uses high fiber counts cable such as ribbon cable with high-density fiber package and smaller outer diameter cable to save the duct space. The cable can use central tube, loose tube and slot core cable structure [28].

4.3.2. Distribution Cable

Distribution cables are connected between the distribution point and access point. According to the location of optical distribution point and access point, distribution cable can choose from outdoor, indoor or multi-purpose cables (outdoor-indoor cable). In general, small fiber counts will be used in distribution cable with duct, aerial or direct bury installation method. Finally, distribution cable requires good midspan access, to perform the task of distributing network usage [28].

4.3.3. Access User Cable

Access user cable connects access point to the terminal device. When the user terminal device is put at outdoor, drop cable can be used as access user cable. Drop cable usually has less than 12 fiber counts fiber and is installed within very short distance. For the drop cable that is accessed to the resident house or apartment, it is recommended to use dielectric cable as drop cable to avoid lighting strike issue [28].

Chapter 5

5. EPON and GPON Evolution

5.1. Technical Challenges in EPON Evolution

The current 1 Gbit/s symmetric data rate supported by the IEEE 802.3-2005 compliant EPON systems has been deemed sufficient for a relatively short period of time and hence upgrading the current EPON deployment is necessary. Along with the initial commercial deployments, service providers started looking for ways of increasing the channel capacity, number of supported customers etc. The increasing demand for the raw bandwidth in the access network and the lack of high-capacity, cost-effective PON system on the market resulted in the preparation of a higher capacity 10G-EPON standard. The future 10G EPON equipment must provide a gradual and smooth evolution path from the currently deployed 1 Gbit/s symmetric equipment. This means that it should support both symmetric and asymmetric data rates, allowing for a straightforward coexistence of various generations of the EPON equipment on the same PON plant, sharing the common physical layer of the network. A number of technical challenges exist when considering a gradual evolution through coexisting of legacy equipment with the 10 Gbit/s EPONs. This means that the active parts of the network (OLT and ONU) need to be replaced [23].

5.1.1. Dynamic Bandwidth Allocation Mechanisms

The Dynamic Bandwidth Algorithm (DBA) mechanism supported currently by the EPON systems will have to undergo some changes. The DBA Agent in the OLT will be responsible for scheduling not one but two mutually cross dependent EPON systems, sharing a single upstream channel. This means the MPCP will have to be slightly changed. The 1 Gbit/s and 10 Gbit/s data path will be separated via WDM multiplexing in the downstream channel, and hence the DBA agent can locate independently each transmission through the GATE message. However, the upstream channel poses more challenges since the clock rates for both the legacy and emerging EPON are different causing jitter concerns in the internal MAC client layer should the DBA operation be based on a single clock rate only. This also means that two MAC stacks will have to be implemented which requires significant extensions to the operation of the DBA agent [23].

5.1.2. Security Considerations

10 Gbit/s EPON systems security threats will be will be identical with those characteristic of all PON network structures in general. Since PON networks uses optical fiber, the man-in-the-middle problem is not commonly considered. Reprogramming the ONU to receive all data the so called "eavesdropping attack" is more serious a problem since this method is completely passive, remotely undetectable, and does not trigger any visible side effect in the network structure or behavior. People may be prevented from tampering with the internal MAC stack implementations with the introduction of Application Specific Integrated Circuit (ASIC) and System On a Chip (SOC) in both ONU and OLT since the said structures are not reprogrammable. They can be customized to allow minimum changes by the systems designer and/or malicious user attempting to alter their functionalities and modify their given operating features. One the other hand the upstream channel is considered more secure due to the network structure and the physical properties of optical fiber channels. The OLT is only aware of the subscribers ONU transmissions and eavesdropping transmission contents from other stations has not been proven practical and until now such vulnerability has not been exploited [23].

5.1.3. Downstream Channel

The next generation EPON will use WDM multiplex technique to send the downstream 1 Gbit/s and 10 Gbit/s data stream thus effectively creating two independent continuous P2MP channels separated by a large bandwidth gap. This allows for uninterrupted operation under any temperature conditions provided that the emerging hardware is operated within the technical specification required by the standard.

The emerging 10 Gbit/s downstream link will most likely be allocated within the 1570 to 1600 nm window depending on the availability of laser sources for OLT and optical filters for the ONU that are compatible with the currently deployed legacy systems. For the physical properties of optical fibers the 10 Gbit/s channel in the 1560+ nm windows is considered a good choice due to limited non–linear impairments and lower 10 Gbit/s signal degradation. Moreover, the 1 Gbit/s downstream link will consequently remain centered at 1490 nm with the 20 nm window size [23].

5.1.4. Upstream Channel

WDM channel multiplexing is not recommended in the upstream channel mainly due to the sensitivity of the Directly Modulated Lasers (DML) to chromatic dispersion outside of the 1310 nm transmission window which is currently utilized by the 1 Gbit/s EPON specifications. The only remaining option is the use of dual rate burst mode multiplexing since modifying the existing 802.3ah standard is difficult. Figure 40 shows both 1 Gbit/s and 10 Gbit/s upstream channel transmissions sharing the same transmission window with legacy systems centered around 1310 ± 50 nm, while emerging systems centered around 1270 ± 10 nm. The dual rate system will add new functionality to the receiver OLT. Besides guaranteeing proper power adjustment via the Automatic Gain Control (AGC) mechanism, it will also have to identify the incoming data rate and maximize receiver sensitivity by adjusting the receiver for each particular burst. However, developing an OLT dual rate burst-mode receiver is a difficult task and will require considerable research to be conduced by the electronics and receiver manufacturers.

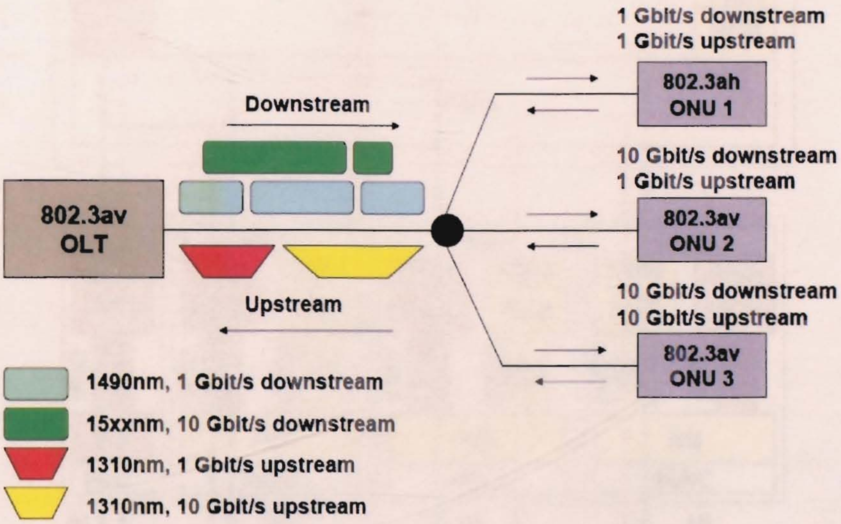


Figure 40: 1/10 Gbit/s downstream, 1/10 Gbit/s upstream representing NG-EPON and legacy ONU's coexisting on the same PON plant.

5.1.5. Dual Rate MAC Stack

The new emerging EPON will need to have both IEEE stacks 802.3av and 802.3ah implemented at least at the OLT side to support the 10 Gbit/s and 1 Gbit/s dual rate upstream transmission. The new IEEE 802.3av OLT requires to support legacy 1Gbit/s, coexistence asymmetric 10/1 Gbit/s and future symmetric 10 Gbit/s ONUs without forcing the service provider for a complete replacement of equipment every time a new ONU is introduced to in the system. For this reason, two full MAC stacks is expected to be implemented on the OLT side while proper implementation of the Tx/Rx paths is required at the ONU side to assume compatible designed data rate. The ONU could implement both MAC stacks (i.e. 1 and 10 Gbit/s ones) for standardization purposes and that only required Rx/Tx paths are activated [24].

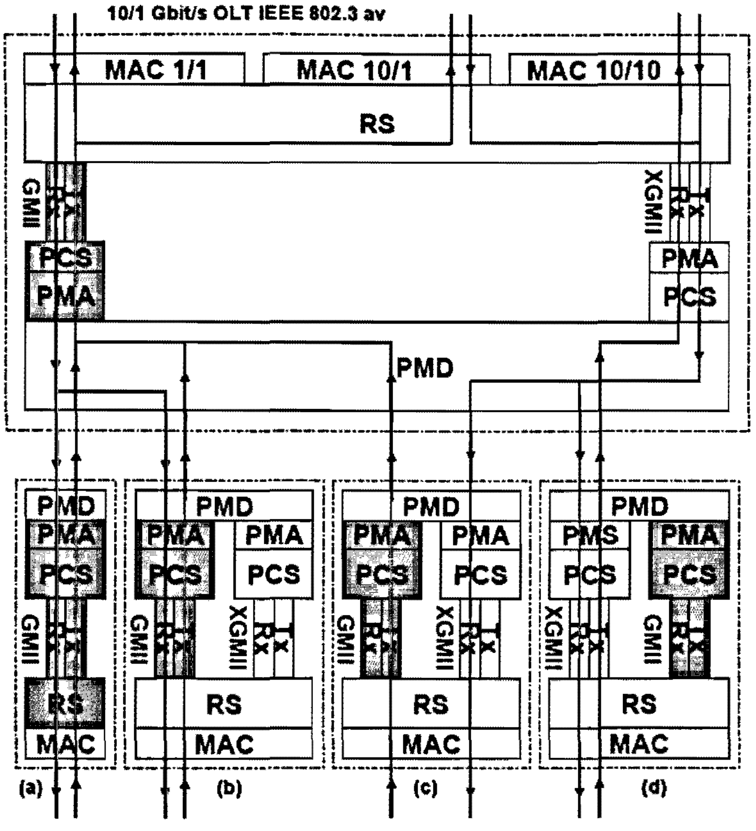


Figure 41: Examples of potential ONU implementation with dual rate MAC stack
Downstream 1 Gbit/s 1490 nm – Upstream 1 Gbit/s 1310 nm
Downstream 10 Gbit/s 1570 nm – Upstream 10 Gbit/s 1310 nm
(a) 1/1 Gbit/s ONU IEEE 802.3ah (b) 1/1 Gbit/s ONU IEEE 802.3av
(c) 10/1 Gbit/s ONU IEEE 802.3av (b) 10/10 Gbit/s ONU IEEE 802.3av

This particular functionality would allow for simplified and seamless migration from legacy into emerging EPON systems, providing a one time upgrade for the OLT card, which would then support any type of connected ONU, regardless of its standard, output data rate, etc.

5.2. Technical Challenges in GPON Evolution

The massive adoption of passive optical networks (PON) in outside plant (OSP) deployments has resulted in a considerable growth in access network capacity required for current bandwidth-intensive applications and consumer-centric services. While GPON meets today's need it is not anticipated to last for long in the passive optical networking world. Eventually more bandwidth will be required by the user and network owners will want to upgrade their networks while continuing to use their existing fiber infrastructure. The standard bodies are looking at different approaches to the next generation of PON, of which two solutions are under consideration by the FSAN. These are the 10 GPON and the WDM-PON. The 10 GPON approach would scale the TDM-PON and the WDM-PON approach would scale the frequency domain. In 10 GPOM, each user will receive the full 10Gbit/s on one wavelength while in WDM-

PON, signals would be sent over 32 different wavelengths (colors), and each ONT on the splitter would receive signals on a different dedicated wavelength. Both approaches are technically feasible, but it isn't yet clear which has the economic advantage and the coexistence with legacy systems advantage. For 10 GPON, the user optical network terminal (ONT) would be very expensive while WDM-PON ONTs would cost less individually but the provider would have to deal with 32 different colors which would raise inventory costs. Universal ONTs with tunable lasers could also be used in WDM-PON applications, but these would be expensive. Putting reflective devices in the ONT might be a lower-cost way to create a universal WDM-PON ONT. PON systems use a single fiber from the central office to a several dozen of users. Because the cost of deploying cables is very expense, the shared fiber architecture has high market penetration mainly due to the additional cost saving over point-to-point networks using the dedicated fiber plants. Hence active Ethernet is generally much more costly and is also unlikely to be implemented in the same cabinet as the existing GPON service [26], [27].

5.2.1. NG-PON: Requirements and Challenges

The popularity that GPON and EPON gained in its massive deployment in regions where dense residence and business users need large capacity leased lines has been exploited. In light of this trend, standard bodies are currently under intensive study of the 10G PON system and WDM-PON systems. A critical requirement is that the emerging 10G PON systems need to be fully backward-compatible with the existing 1G PON and analog video overlay infrastructures that have already been deployed in the field. This will allow coexistence and smooth migration from the 1Gbit/s to 10 Gbit/s systems utilizing the same fiber plant. As a result, carriers will have the necessary flexibility to deploy/upgrade to faster services over NG-PON whenever needed and would maximize the return on investment and life cycle of existing fiber systems. Many other requirements comes into play when considering the technical difficulty and economic feasibility of implementing 10 Gbit/s PON systems and these include tight link power budget, transmission distance, burst-mode transmission, and necessity of compatibility with legacy data and video systems. These impose tough requirements on physical layer chipsets that have to operate under stringent system constraints [27].

	IEEE 802.3av 10G EPON	**ITU-T/FSAN 10G GPON**
Downstream Rate	10G	10G
Upstream Rate	1G (Asymmetric) or 10G (Symmetric)	2.5G (XG-PON1) 10G (XG-PON2)
Downstream wavelength	1575 – 1580 nm	1575 – 1580 nm
Upstream wavelength	1G: 1260 – 1360 nm (same as 1G EPON) 10G: 1260-1280 nm	2.5G: TBD Choices: C, L, O+, O- (Same to 10G EPON) 10G: TBD Likely: 1260 – 1280 nm
Link Budget	20, 24, 29 dB	Class B+: 28dB; C: 30dB; C+: 32dB
FEC required?	1G: Not needed 10G: Mandatory	2.5G: Likely not 10G: Mandatory

Table 11: 10G EPON and 10G GPON comparison table

5.2.2. Technological Challenges in NG-PON Transceivers

To satisfy the system link budget requirements the optical transmitter power and receiver sensitivity has to be increased. This requires the use of highly sensitive PIN or avalanche photodiode (APD) with low noise pre-amplification ICs. Upstream burst mode optical transmission is still an active area of development. 10Gbit/s upstream channel poses extra improvement to key elements to both burst mode laser driving circuit and burst mode optical receiving circuit. The increase of the signal's rate causes the sensitivity of optical receivers to decrease. Hence to compensate for loss of optical sensitivity, forward error correction (FEC) and high-power transmitters have to be employed to meet the high power budget requirement. 10G PON specification requires the use of FEC to be mandatory on both symmetric and asymmetric operation configurations. The ONU transmitter will then have to meet basically two requirements. First, for developing high split ratios the fast switching and initialization is very important, particularly for the quick recovery of the traffic after network failure which affects a number of ONUs. Second, the fast tracking of slow power drift is also needed which is important for long packet transmission. On the other hand the OLT is required to have low sensitivity, wide dynamic range, and a fast response for flexibility in network deployment. The signals arriving to the OLT from different ONUs could have large difference in transmission loss, depending on how far it is located down the link. Due to coexistence of 1G and 10G signaling in the upstream, the OLT receiver must have a fast response to amplitude variation and a short settling time. Several network operators have already shown interest in the WDM-PON for longer term implementations as it provides virtually P2P connectivity through the dedicated wavelength. It also has the advantage of being protocol transparent, unlimited bandwidth, security, and simplicity in electronics. Hybrid WDM/TDM-PON could increase the split ratio without the significant increase of optical loss due to splitting loss in the remote node. The next sections will discuss the two most considered evolution paths for GPON, 10G GPON WDM/TDM [26].

5.2.3. 10G GPON Issues

10G GPON is relatively expensive because the transceivers have to support a 20Km range over 32 splits. Not to mention the availability of 10G GPON is a key drawback as more work needs to be done before this can be considered a feasible option. Another drawback is interoperability with existing technology like GPON. Also, at 10Gbps on the feeder fiber, it is still only half the available aggregate bandwidth of today's WDM-PON. By the time 10G GPON is commercially and feasibly available, WDM-PON will likely be up to 80Gbps (32x2.5Gbps) on the feeder fiber. If we consider TDM-based PONs will have to be upgraded on an average of every five years following the rate of consumer bandwidth growth, WDM-PON provides a future proof PON system [27], [29].

5.2.4. WDM-PON Issues

WDM-PON seems to be the only viable and feasible solution for upgrading GPON. It uses the best elements of point-to-point networks which is security and dedicated bandwidth. It also uses the best elements of PON which is low infrastructure cost due to fiber sharing and passive components in the outside plant which reduces operating cost. Others argue that WDM-PONs technology is expensive, not standardized, too large for high density applications or inefficient use of bandwidth. Although some of these points holds true in the existing systems today, the future potential of the technology can easily overcome these concerns. Today current WDM-PON systems are more expensive than GPON, but they also provide 16 times more bandwidth. But it is anticipated that cost reductions are occurring as the technology becomes more widespread and that the equipment cost will also reduce with volume deployments. However, standardization remains a critical issue for 10G GPON to guarantee interoperability between different vendors. In the event that the wavelength plan should ever be changed to accommodate further standardization, WDM-PON systems that employ "colorless" optics technology would slightly be impacted as the change would only affect the Arrayed Wavelength Grating (AWG), a device that determines the wavelength plan, rather than the ONUs or OLT line cards. The AWG is also responsible for multiplexing/demultiplexing the wavelengths into and out of the feeder fiber. Migrating from GPON to WDM-PON offers the simplest upgrade path for GPON with the least amount of service impact. Instead of using the traditional Planar Lightwave Circuit (PLC) splitter to multiplex and demultiplex wavelengths between the feeder fiber and the distribution fibers WDM-PON uses AWG. The AWG in a WDM-PON system that uses "colorless" optics is also responsible for spectrally slicing a seed light, generally provided from the OLT, into the individual wavelengths that are passed to the ONTs. The AWG can further be packaged in the same form factor as the existing PLC splitters which allow service providers to insert the module inside an existing GPON splitter cabinet to support WDM-PON [25].

5.2.5. The Evolution of GPON

After some initial deployment of BPON, the industry realized that a BPON ODN could not be incrementally upgraded to the next-generation technology, GPON. Consequently, it was a requirement from the early days of GPON development that next-generation upgrade be incrementally possible on the same ODN. Although GPON offer enough capacity for today's customers, the Next Generation GPON systems (NG-PON) are evolving to future-proof the investment of currently deployed GPONs and fiber infrastructures. Other basic requirement for NG-PON is to re-use the GPON protocol, components and infrastructure besides offering higher capacities [27].

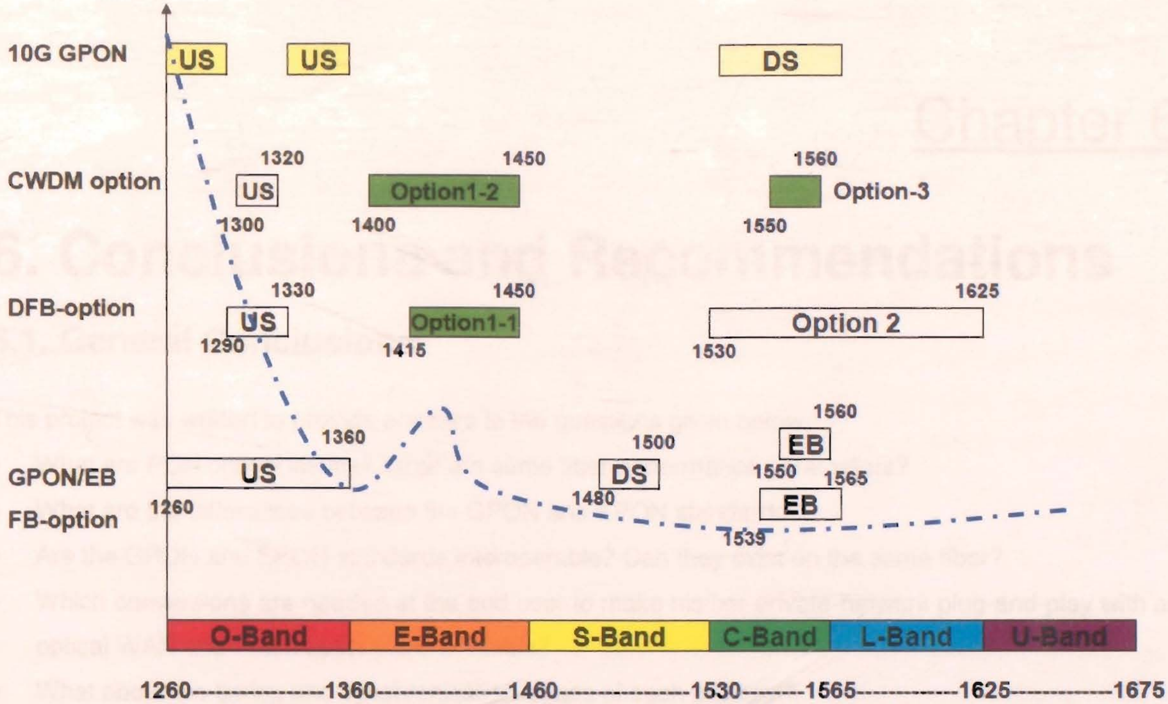


Figure 42: Wavelength allocation for GPON (including G984.5 option B) and NG-PON
DS: Downstream, US: Upstream, EB: Enhancement Band,
DFB: Distributed Feedback Laser, FP: Fabry-Perot Laser

The GPON evolution as depicted in the above figure defines two evolution stages: The first step, NG-PON1, is compatible with GPON deployments in accordance with the wavelength plan of G.984.5. two candidates are defined: XG-PON1, asymmetric GPON supporting 10 Gbps DS, and 2.5 Gbps US. XG-PON2, symmetric GPON supporting 10 Gbps both DS and US. A WDM option to overlay multiple GPONs and/or point-to-point overlays with different wavelengths (i.e. WDM) on the same fiber infrastructure as defined in G.984.5 enhancement bands. The second step, Next Generation PON 2 (NG-PON2), recognizes higher capacities and more wavelengths and hence, NG-PON2 is not constrained by the current GPON ODN. Also, new modulation formats, such as OFDM and code division multiplexing (CDM) are discussed for NG-PON2 [29].

Chapter 6

6. Conclusions and Recommendations

6.1. General Conclusions

This project was written to provide answers to the questions given below.

- What are PON critical issues? What are some fiber performance parameters?
- What are the differences between the GPON and EPON standards?
- Are the GPON and EPON standards interoperable? Can they exist on the same fiber?
- Which conversions are needed at the end user to make his/her private-network plug-and-play with an optical WAN and which options are available?
- What about the timing and synchronization issues of each protocol?
- How can GPON and EPON be implemented into new projects?
- What are the challenges of each standard evolution?
- What are the options of each standard evolution? How viable and feasible each of them?
- What kind of cables used in FTTx deployment? What are some of their characteristics?
- What are some integration, test and management criteria?

6.1.1. Differences between GPON and EPON

The differences between GPON and EPON can be found at many different levels. GPON protocol is flexible since it provides ATM service and additional services like GEM with several possibilities for data encapsulation. The EPON standard uses the Ethernet stack; hence the service provided by EPON is Ethernet. Like ATM or GEM, Ethernet is capable of encapsulating other protocols. The network layer of GPON uses its own frame format to transfer the data. Currently GPON has the fastest transmission speed followed by EPON. The transfer speeds for EPON and GPON might be upgraded to higher speed. A more detailed analysis for a given FTTx network highlights GPON's significant advantage over EPON. This is due to GPON's higher split ratio, line rate, bandwidth efficiency and multiple protocol/services support which results in a reduction in the amount of OLT equipment by more than a factor of 2 over EPON. This also translates into significant space and power reduction at the central office as well as life cycle cost savings due to the reduction in the OLT equipment. GPON also offers equipment interoperability through FSAN and ITU initiatives. On the other hand, the acceptable price of EPON from vendors has enabled providers to deploy residential PONs in mass in certain countries. GPON standard provides native carrier class transport of both Ethernet and TDM and thus has a single cost-effective PON technology for both residential and business service. However, if TDM service is not required, EPON might look more attractive.

6.1.2. Interoperability

To provide the best solutions to different users in large networks it may be desired to use more than one standard. However there are interoperability problems when using more standards in a single network. It is inefficient for a network that needs equipment which meets the requirements of two or more standards. A second problem is the different band-plans of each standard conflict with each other. As a result the interoperability of the two standards here isn't possible without any modification in the specified band-plan.

6.1.3. Plug-and-play Options

Plug-and-play implies that existing equipment needs none or minimum modifications when it is connected to new hardware. Nowadays user equipment like IP-phones, Internet, and even televisions have an Ethernet interfaces. Based on this information a standard which supports Ethernet should be the best choice. Both GPON and EPON provide an Ethernet service, GPON with some extra conversion and EPON without any conversion. For a plug-and-play system EPON should be the easiest implementation.

6.1.4. Physical Differences

On the physical level there are differences in the available data rates, and device timing requirements. The EPON standard specifies relaxed timing requirements compared to the GPON specifications. The GPON stringent specifications make the physical devices more expensive to produce. For the available data rate GPON is currently the leading standard. However a 10 Gb/s Ethernet stack is available for an active optical network, and will be available on PON soon. With easy to implement timing specifications and a possible transfer speed of 10 Gb/s EPON is suitable for low cost high speed PONs.

6.1.5. The Evolution

When service providers consider the evolution of their GPON/EPON networks, the following factors must be considered:

1. How easy is it to implement each technology?
2. How future-proof is each technology?
3. How cost-effective is each technology?

WDM-PON is the only technology that addresses all three of these issues in ways that improve the service provider's competitive and financial positions. Co-exiting with GPON is one of the most attractive features as service providers can leverage existing assets to upgrade customers one at a time without affecting the service of other subscribers on the network. It is anticipated that networks will eventually evolve to all IP; service providers can then service subscribers who are early adopters of IP-based, residential gateways while still leveraging the service provider's existing network infrastructure. On a per Mbps basis, WDM-PON is the most cost-effective technology available today. On a per subscriber basis, WDM-PON can compete with GPON cost and it is expected that the price will even drop further to a competitive cost after massive deployments while offering 16 to 32x more bandwidth on the feeder fiber. In conclusion, WDM-PON represents the easiest, most future-proof, and cost effective strategy for upgrading GPON networks. 10 Gbit/s EPONs and GPONs will deliver much more bandwidth to the end–subscribers, when compared with current (legacy) equipment and CATV network using the DOCSIS 3.0 protocol, making it a good replacement architecture candidate for next generation CATV networks [25].

6.2. Recommendations

6.2.1. New Project Implementations

When implementing a new project support for the most common services should be taken into account. From the end user point of view an ONU hardware equipped with an Ethernet interface should be most convenient to provide these services. Such system implementation that requires less protocol conversion or encapsulation would be an EPON based system. Since the Internet protocol has been there for a while and lots of services are born in this environment, the migration of these services to a PON network using the same protocol has its advantages. GPON on the other hand has its advantages as well; it provides more direct service interfaces, but the main question remains would an average user really needs those different services. At the user level if the same service could be viable using Ethernet, ATM support becomes extra. Since the user equipment is standardized to Ethernet, ATM is no must, extra conversion like Ethernet to GEM and vise versa are then overkill. At the network operator level the advantage of EPON is the relative cheap equipment needed for EPON networks. A general recommendation to any new project is to consider the required services and the available protocols that support these services taking into consideration the techno-economic factors behind the implementation of any of the two standards in a PON environment.

6.2.2. Future Work

It is clear by now that any emerging standard should take into consideration legacy systems and should offer coexistence and smooth migration to the next generation PONs. Although current standards describe a more or less complete PON network based on EPON and GPON there are still unsolved issues. What happens when the 10Gbit/s systems exist side by side with the legacy 1.2 / 2.4 Gbit/s systems? The 10Gbit/s rates are available for active optical networks now, but are they suitable for PONs? Are the devices then still easy to manufacture? Or more constraints need to be implemented pushing the price even higher? These questions can only be answered and analyzed when the standards are available. IEEE 802.3av 10Git/s EPON standard answered some of these questions while network operators still wait for ITU-T 10G bit/s GPON standard which is expected to come out on or before 2012. Another question that is unanswered to any new project, what if more wavelengths are going to be used in a standard? Each standard describes a fixed band-plan to use but can this bandplan be extended with other wavelengths?

6.2.3. Personal Observations and Opinions

FTTx is a technology that every service provider will have to implement eventually. From all the FTTx flavors, FTTH is the most future proof solution since DOCSIS 3.0 and VDSL2 has a limitation of 100Mbps. Only fiber offers symmetric 100Mbps or higher without distance or interference constraints. FTTC+VDSL2 CAPEX consists mainly of street cabinets, power supply and network equipment, which are not re-usable as part of a FTTH deployment. As very few of FTTC CAPEX can be re-used for FTTH, FTTC is not a "first step" to FTTH. In my opinion if a decision needs to be taken as regard to which FTTx type to be used, FTTH is the way to go. All new infrastructure deployments must be fiber since the CAPEX required for copper infrastructure cost the same as fiber infrastructure. Moreover, fiber in the last mile solves the issue of bandwidth bottleneck for the end-user. Now which architecture should be considered? P2P is more secure, dedicated but not efficient use of bandwidth. On the other hand P2MP is the most CAPEX efficient (lower duct occupancy with less fiber) and saves OPEX at the central office, with no foreseeable limit in available bandwidth. However more work needs to be done on the security concerns. So for corporations P2P is still the best choice but for residential and small offices, FTTH is the best choice since it offers a reasonable security level and the broadcast nature of P2MP best supports the video overlay on the enhancement band. Deploying a FTTH infrastructure takes time, resources, and the skills of a fixed local loop operator. Hence access to every civil engineering infrastructure in the public domain is critical as well sharing of the terminal part of the fiber to the customer's premises since landlords and building managers will probably refuse to grant access to more than one operator so sharing of the last part of the optical fiber local loop among operators is necessary. In my opinion every operator looking at deploying FTTH should gradually move into massive deployments. Hence pilot projects and pre-rollout projects become crucial before mass market rollout. Now which standard to apply when deploying PON in the access network? In dense residential areas where fast internet services are the major customer requirement, EPON is the best choice. EPON offers economic advantages in terms of installing, managing and delivering services to a subscriber population. Capital investment in EPON structure yields a short term return. EPON provides carriers with a new and economically competitive Ethernet platform which is less complex and easier to manage both for subscribers as well as service providers. With metro networks employing Ethernet based solutions, access network should be able to carry Ethernet compatible transmissions between subscriber and metro without additional protocol overhead as imposed by GPON standard. For these reasons I believe EPON is currently the best platform for service providers to deliver fast and gigabit Ethernet to customers than GPON. Furthermore, GPON technology requires more complex chips and additional 1Mb external buffer memory is required which results in longer development cycle and higher chip cost. But for businesses that require direct ATM service support, GPON offers such platform and hence would be favorable over EPON. In my opinion a market research is very important to determine which services are on high demand before deciding which standard to use. A service provider could implement GPON in areas where Ethernet and ATM are on high demand and EPON in other areas where Ethernet is on high demand. ATM requirement is decreasing and even the GPON standard has gradually taken out the ATM support in the new standard amendments since most of the GPON deployments are Ethernet based (GEM). For this reason I believe EPON offers a better long term standard than GPON.

6.2.4. Final Thoughts

- New infrastructure in the access network is required to meet bandwidth needs.
- Regulations have set a proper environment for FTTH adoption.
- Fiber has many advantages among which are enormous bandwidth, no cross talk, and high signal security.
- There are basically two categories for optical network: AON and PON.
- PON infrastructure is less expensive, efficient bandwidth utilization and offers high split ratio. Hence the cost of civil works is split amongst all end-users on the same PON.
- There are many different options for the access network: " FTTB, FTTC, P2P, EPON, GPON"
- No one answer: choice depends on specific operator deployment situation
- All choices involve major investment in fiber infrastructure.
- Meanwhile researchers will continue to invent new optical boxes.
- In 2012 ITU-T will finalize the 10GPON standard, will there continue to be many options or will a clear winner emerge?

- EPON platform offers a win-win situation. Cheaper installation, operation and management for service providers and cheaper ONT for clients.
- EPON offers native transport of Ethernet frames.
- EPON supports true Ethernet switching: – Fully Compatible with IP – Supports TLS – Broadcast, Multicast, and IGMP.
- GPON has complex mixed mode traffic implementation and higher cost of optics.
- GPON can operate at different rates with different transceivers.
- GPON can be configured in asymmetric fashion and take advantage of lower ONT laser costs. (eg.1.2G/622M or 2.4G/622M)
- GPON has complex layering model Ethernet/GEM/GTC encapsulation and hence complex management.
- Co-existence between G/E-PON and the next-gen PON in the same ODN is desirable for the effective use of the fiber resource and helps save construction investment.
- Several technical candidates for NG-PON of which three are being considered: 1 - Higher speed TDMA-PON, 2 - WDM-PON, 3 - Hybrid WDM-TDMA PON.
- Higher speed TDMA-PON uses high speed burst mode transceiver. (10Gbps direct modulated laser DML)
- WDM-PON uses colorless light source, tunable laser, high power BLS (broadband Light Source) and AWG.
- Hybrid WDM-TDMA PON uses a mix of both components.
- WDM-PON seems to be the best evolution path for current EPON and GPON systems, but the cost of WDM-PON equipment is still a major stumbling block to widespread deployments.
- WDM-PON is still not standardized, and that puts it at a disadvantage compared with the higher speed TDMA-PON.
- How can 10G PON be cost effective? One possibility the use of low power / sensitivity components at ONT, better at OLT.
- 10G-PON has an advantage in terms of standardization, maturity, cost and power consumption.
- WDM-PON can offer higher bandwidth and reach and additional advantages with respect to Security because of dedicated wavelength per subscriber and Management since point-to-point systems are typically easier to manage than point-to- multipoint systems (e.g. fault handling).
- Thus, the trend is that 10GPON is envisioned for residential applications while WDM-PON is investigated for business or bandwidth intensive backhaul.

Appendix A

Optical Communication Review

1. Fiber Communication Systems

A path is needed to transmit data from one point to another. To create such path a medium is needed to transfer the data. Depending on the requirements and available infrastructure the media can be air, copper or optical fibers. With these media, radio networks, electrical networks and optical networks can be created.

In this project optical networks will be discussed. Optical networks use switching and routing equipment as in electrical networks. With this switching and routing equipment optical networks can be configured in different ways, two examples are a passive or an active configuration.

Active networks are built with routers and switches which have their own power supply. While in passive networks the routers and switches don't have external power supplies. [18],[17]

2. System Design Consideration

The main system-level components of a fiber optic data link are the fiber Optic transmitter, the fiber and the fiber optic receiver. For Digital system the performance parameters are data rates and bit error rates, while analog systems are bandwidth linearity and signal-to-noise ratios. For all systems, transmission distance is the main parameter. [18],[17]

Many factors affect how far one can transmit over fiber. The main factors are

→Transmitter optical output power

→Operating wavelength

→Fiber attenuation

→Fiber Bandwidth

→Receiver optical sensitivity

3. Rise Time Budget

The components in the same link must be turned on and off fast enough. Fiber dispersion must be low enough to meet the bandwidth requirements of the application. Rise time (bandwidth) for the receiver may be limited by either the rise time of the components or the bandwidth of the RC time constant. [18],[17]

The system rise time can be derived from the below equation once all the necessary component rise time has been determined:

$$T_{sys} = 1.1 \sqrt{t_{r1}^2 + t_{r2}^2 + \ldots\ldots\ldots\ldots + t_m^2}$$

The bandwidth of system can be derived from $t_r = \dfrac{0.35}{BW}$

4. Optical Link Loss Budget

The receiver optical loss range or optical dynamic range taking into account losses along the path:

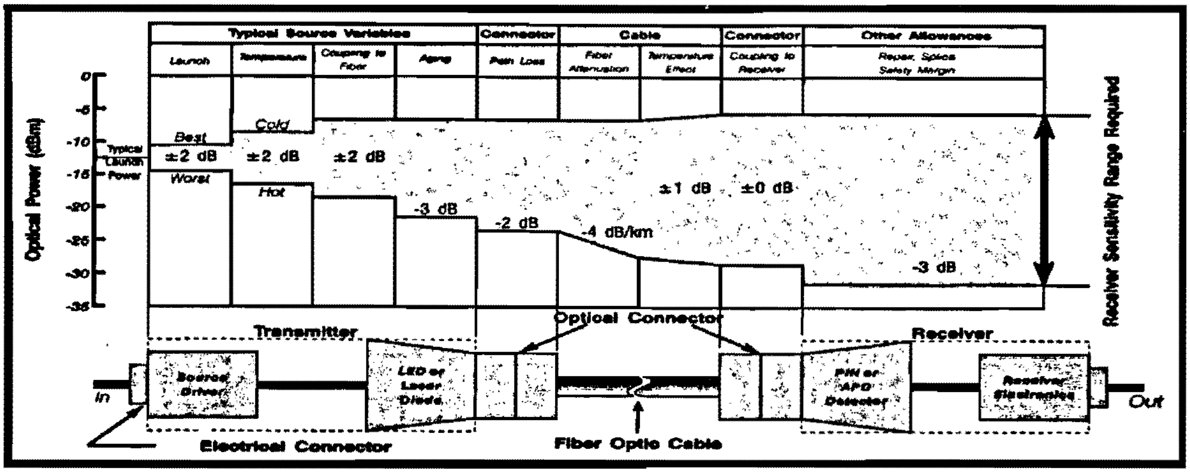


Figure 43: Optical Link Loss Budget (Source: National Dong Hwa University – Fiber Technology)

5. Sensitivity Analysis

The minimum optical power that must be present at the receiver is called Sensitivity analysis.

Source Intensity Noise: Two main types—phase noise and amplitude noise.

Fiber Noise: Is referred to as noise generated in fiber due to dispersion, fiber nonlinearity.

Receiver Noise: Includes noise generated in the photodiodes, the conversion resistor, and the amplifier. Shot noise is the dominant form of receiver noise

Time Jitter and Intersymbol Interference:

Signal To Noise Ratio: It is a common way to express the quality of the signal in a system. [18],[17]

SNR = $\frac{S}{N}$ Expressed in dB, the equation can be written as SNR (dB) = $10 \log_{10}\left(\frac{S}{N}\right)$

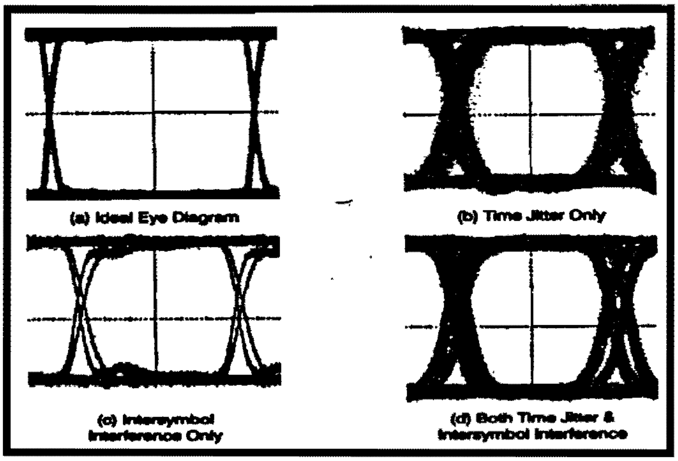


Figure 44: Eye Diagram (Source: National Dong Hwa University – Fiber Technology)

6. Bit Error Rate

Bit error rate of a system can be estimated as follows:

$$BER = Q\left[\sqrt{\frac{I_{min}^2}{4N_oB}}\right]$$

No = Noise power spectral density (A2 / Hz)

Imin = Minimum effective signal amplitude (Amps)

B = Bandwidth (Hz)

Q(x) = cumulative distribution function (Gaussian Distribution)

BER and SNR are interrelated; the better SNR yield a better BER. [18], [17]

7. Modulation Schemes

The process of passing information over the communication link typically involves three steps: encoding, transmitting and decoding the information. Encoding is the process that modifies the information from the source so that it can be carried by the communication medium. [18], [17].

8. Dispersion

Light is sent down the fiber in the form of a pulse. As pulses travel down the fiber they spread out. This spreading is known as dispersion. Dispersion is undesirable because it can cause bit errors when the signal reaches the receiver. To avoid bit errors, it is desirable to use dispersion compensation or to regenerate the signal using a repeater. The signal must be regenerated prior to the occurrence of any errors. Different wavelengths of light will travel at slightly different speeds in optical fiber, due to the variation of refractive index with wavelength. Therefore two pulses carried on two different wavelengths, will arrive at the destination at two different times. The time difference is very small and measured in picoseconds, but it can pose problems for receivers. Figure 45 shows how a square pulse of light becomes attenuated and deteriorates into a classical "eye pattern" as it propagates down the fiber and is affected by attenuation and dispersion. (Note that the fixed displacement in time caused by dispersion is different from the low frequency and high frequency shifting in time caused by jitter. However, the optical receiver is presented with similar challenges for recovery of the data) [21].

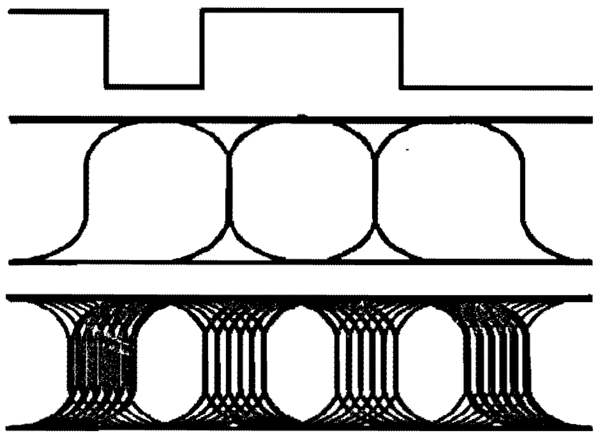


Figure 45: Typical Eye Pattern

Chromatic dispersion is not a significant factor for products operating at frequencies up to 270Mbs (like SDTV). But for higher frequencies over 1Gb/s, dispersion affects needs to be considered. Dispersion becomes critical when the time difference between the arriving signals is a significant percentage of the period of the clock rate being used, because the optical receiver will not be able to distinguish between one bit and the next one. 1 bit is transmitted in 673ps (the period of one bit) for HDTV with the bit rate of 1.485Gb/s. The maximum allowable jitter in HDTV is 0.2u.i. as defined in SMPTE292M, where u.i. is the period of 1 bit. (In practice, 0.2u.i. is not easy to achieve without incurring a high price penalty, and many of today's HDTV devices exceed these jitter specs). In fiber optics we practically use 0.3u.i as the maximum tolerable dispersion and the maximum permissible "Dispersion Jitter" for HDTV can be calculated at 0.3u.i. x 673 = 201.9ps. For SDTV the same calculation is reveals 1,110ps. FWHM (Full Width Half Max) for FP lasers is typically 4nm while for DFB lasers it is typically 0.2nm. Chromatic Dispersion (CD) at a particular operating wavelength is measured in ps/nm.km. For standard Corning SMF-28 optical fiber this is around 2 for 1310nm and around 17 for 1550nm.

CD = ps/nm.Km or Km = ps/CD.nm

The following table uses the above formula and values to derive maximum distances in km referable to Chromatic Dispersion. (Note that these distances are theoretical values for dispersion only. Other characteristics, such as the fiber attenuation, will generally have more influence as limiting factors and many of the distances quoted will never be attainable).[21].

	Fabry - Perot		**DFB**	
	1310 nm	**1550 nm**	**1310 nm**	**1550 nm**
HDTV	25Km	3Km	500Km	58Km
SDTV	137Km	32Km	2,750Km	323Km

Table 12: Theoretical chromatic dispersion limits – some of which are unachievable

Appendix B

GPON and EPON Tx launch power. Referring to 1G EPON and GPON

→ 1.25G/1.25G EPON optics:

• PX10: 1310nm (ERmin 6dB, Pmin -1dBm) (ER=Extinction Ratio = P_1/P_0)
    1490nm (ERmin 6dB, Pmin -3dBm)

• PX20: 1310nm (ERmin 6dB, Pmin -1dBm)
    1490nm (ERmin 6dB, Pmin +2dBm)

→ 2.488G/1.244G GPON optics:

• Class B: 1310nm (ERmin 10dB, Pmin -2dBm)
    1490nm (ERmin 10dB, Pmin +5dBm)

• Class C: 1310nm (ERmin 10dB, Pmin +2dBm)
    1490nm (ERmin 10dB, Pmin +3dBm)

• Class B+: 1310nm (ERmin 10dB, Pmin 0dBm)
    1490nm (ERmin 10dB, Pmin +4dBm)

Overall Pmin of +1 to +5dBm is reasonable. Future trends count on on-chip integration of SOA gain with min. cost premium. 1Gb/s ROSA (Receiver Optical Sub-Assembly) performance has improved over time 1500-1550nm.

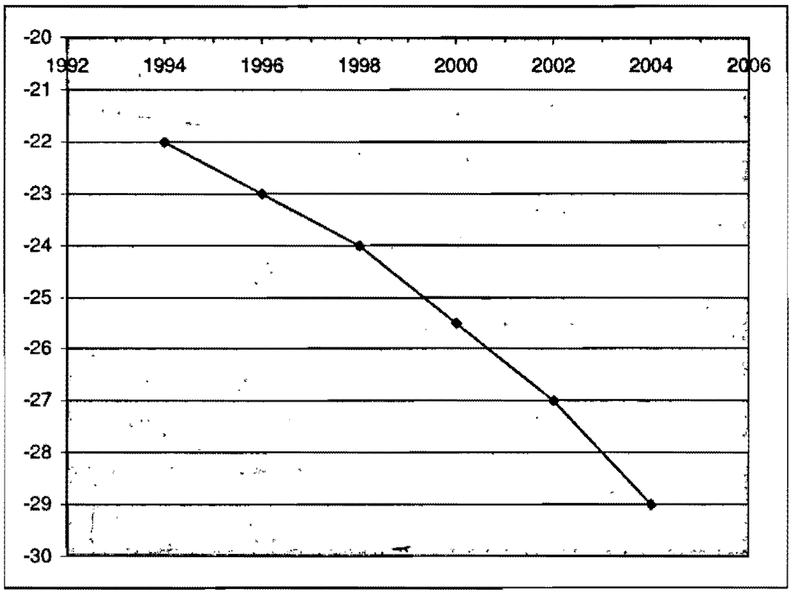


Figure 46: Sensitivity over time (dBm)

10Gb/s ROSA Sensitivity improvements are possible by better controlling noise, jitter and bandwidth; and taking advantage of equalization techniques. Experience at the 1Gb/s level has shown that raising the bar simply provides manufacturers with a goal to meet, and has the overall effect of speeding up development.

Appendix C

The section summarizes IEEE 802.3av 10GEPON PHY wavelength allocation.

Band	Wavelength [nm]
O-Band	1260 – 1360
E-Band	1360 – 1460
S-Band	1460 – 1530
C-Band	1530 – 1565
L-Band	1565 – 1625
U-Band	1625 – 1675

Wavelength Allocation - DS

- 10GEPON should take in account existing GEPON
- 10GEPON should support presence of RF Video
- 10G Downstream:

  - 1st choice 1560nm and above

    Advantages:

    - Mature technology

    - Available today for SDH/SONET 10 Gbit/s system with multiple vendors

    - Easy to achieve modulation speed

    - Available as Laser Diodes and as Optical Amp (EDFA)

    Disadvantage:

    - In some cases optical Band Pass filter will be needed at the ONU

  - 2nd choice 1530-40nm

    Advantages

    - Same as 1560nm

    - ONU doesn't need optical Band Pass filter

    Disadvantage

    - May collide with the Upstream

Wavelength Allocation – US

- 10G Upstream

  - 1st choice is 1310nm

    - Fiber attenuation is 0.5dB/km ie. 10db for 20km

    - Widely available lasers

    - Time division multiplexing with 1G at OLT

  - 2nd choice 1530-40nm

    - Fiber attenuation is 0.3dB/km ie. 6db for 20km

- Lasers are available, but might be more expensive
- No shared DBA between 1G and 10G upstream at OLT

Note that 1530nm offers additional 4dB for the Optical Budget and is available in the market for 10G applications. Additional wavelength increases the upstream throughput in a mixed network.

As to optical Budget, 29dB is the most common request optical budget. 10GEPON should adapt the Worse Case scenario of GEPON Optical Budget with FEC. FEC "expands" the optical budget by about 3dB with R-S. This relaxes the optics requirements.

Summary

- Wavelength plan

- Upstream – 1310nm (1G)
- Upstream – 1530nm or 1310nm (10G)
- Downstream – 1490nm (1G)
- Downstream – 1550nm (Video overlay)
- Downstream – 1565nm (10G)

- Optical Budget

- 3 Classes
- Class I TBD
- Class II 24-26dB
- Class III 29dB

FEC could improve the Optical Budget by 3dB.

Appendix D

Outline of ITU-T G.984.x standard:

No.	Outline	Approved
G.984.1	GPON Service requirements	Mar. 2003
G.984.2	GPON interface between OLT-ONT physical layer specifications	Mar. 2003 Feb. 2006 Amd1
G.984.3	GPON interface between OLT-ONT TC layer specifications	Dec. 2003 Mar. 2006 Amd2
G.984.4	GPON ONT management and control interface regulation	Jun. 2004 Mar. 2006 Amd2
G.984.5	Enhancement band of GPON	Jun. 2007 (consent)

The 10G GPON white paper has been released in Q4 of 2008. The physical layer specifications of XGPON1 have been dealt with. ITU-T speeds up the standardization process for 10G-GPON. G.987.1 and G.987.2 (PHY) recommendations are scheduled to be consented and then published in next SG15 plenary, in Sept., 2009, G.987.3 and .4 recommendations are scheduled to be consented and then published in the plenary in Sep, 2010.

- **Generation 0**: Research projects a-plenty
- **Generation 1**: STM-PON (ITU G.982: 50 Mb/s TDM, based on static time slots)
- **Generation 2**: ATM-PON (ITU G.984: 155/622 Mb/s TDM, based on ATM cell transmission)
- **Generation 3**: EPON and GPON

  IEEE 802.3ah: 1Gb/s TDM, based on Ethernet frame transmission

  ITU G.984: 2.4/1.2 Gb/s TDM, based on GEM fragment transmission
- **Generation 4**: 10G-EPON, XG-PON
- **Generation 5**: ?

Item		**10G GPON**	**10G EPON**	**WDM PON**
Ultra-broadband	DS Bandwidth	10 Gbps shared	10 Gbps shared	1 Gbps/λ individual
	US Bandwidth	2.5Gbps shared; 10Gbps shared	1 Gbps shared; 10Gbps shared	1 Gbps/λ individual
Convergence		Possible	Possible	Possible
EPON Compatibility	Possibility	Yes but complex	Yes	Yes
	ODN Protection	Untouched	Untouched	Touched
	Service Interruption	Yes	Yes	No
GPON Compatibility	Possibility	Yes	Yes but complex	Yes
	ODN Protection	Untouched	Untouched	Touched
	Service Interruption	No	Yes	No

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