GPON

INSTALATION, COMMISSIONING, AND TESTING OF FLEXLIGHT SOLUTION

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Abstract

This document introduces the concept of Passive Optical Networks and provides an explanation of BPON and EPON standards. A separate chapter, based on ITU-T G.984 recommendations, is dedicated to a comprehensive explanation of the GPON standard.

Also, the FlexLight GPON solution is introduced and a description of the equipment available in the MINT Lab, including the possible configurations, commissioning, testing, troubleshooting and QoS features is given.

Since there is no manual for the FlexLight network management system version 2, a user guide was compiled and is included in this document. This version was preferred because is providing a more user friendly access of the FlexManage monitoring, control and maintenance capabilities over the PON.

This document was written as a reference manual for the MINT Lab. It is our hope that it will benefit future students which are interested in this new technology.

Acknowledgements

We would like to thank Dr. M. H. MacGregor for giving us the opportunity to work on this emerging technology. His continuing interest in providing the MINT Lab with the latest equipment will greatly benefit future graduates of the University of Alberta Master in Internetworking program.

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List of Abbreviations

10G-EPON	10 Gbps Ethernet Passive Optical Network
AAL	ATM Adaptation Layer
ADSL	Asymmetric Digital Subscriber Line
ADSL2+	Asymmetric Digital Subscriber Line 2+ (ITU-T G992.5)
AE	Active Ethernet
AES	Advanced Encryption Standard
Alloc ID	Allocation identifier
ANSI	American National Standard Institute
APD	Avalanche Photodiode
APD-TIA	Avalanche Photodiode Trance Impedance Amplifier
APON	ATM Passive Optical Network
APR	Address Resolution Protocol
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BBE	Background Block Errors
BE	Best Effort
BER	Bit Error Rate
BIP	Bit Interleaved Parity
B-ISDN	Broadband Integrated Service Digital Network
BM-CPA	Burst Mode Clock and Phase Alignment
BM-LDD	Burst-Mode Laser Diode Driver
BM-RX	Burst Mode Receiver
BPON	Broadband Passive Optical Network (ITU-T G.983)
BW	Bandwidth

CAPEX	Capital Expenditures
CATV	Cable Television
CBR	Constant Bit Rate
CES	Circuit Emulation Services
CIF	Metro network interface card
CO	Central Office
CoS	Class of Service
CRC	Cyclic Redundancy Check
CSMA/CD	Carrier Sense Multiple Access / Collision Detection
C-VID	Customer VLAN Identifier
C-VLAN	Customer Virtual Local Area Network
CWDM	Coarse Wavelength Division Multiplexer
DBA	Dynamic Bandwidth Assignment
DBR	Dynamic Bandwidth Report
DES	Deserialiser
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name System
DOCSIS	Data over Cable Service Interface Specifications (DOCSIS 3.0 - ITU-T J.222)
DS	Downstream
DSCP	Differentiated Service Code Point
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DWDM	Dense Wavelength Division Multiplexing
EF	Expedite Forwarding
EFM	Ethernet in the First Mile (IEEE 802.3ah)

EqD	Equalization Delay
EPON	Ethernet Passive Optical Network (IEEE 802.2ah)
ES	Errors per Second
FCS	Frame Check Sequence
FE	Fast Ethernet
FEC	Forward Error Correction
FiOS	Fiber Optic Service
FTTH	Fiber to the Home
FTTX	Fiber to the X (curb, premises, building, office, home)
GbE	Gigabit Ethernet
GBE	Gigabit Ethernet Card
GBR	Guaranteed Bit Rate
GEM	GPON Encapsulation Method
GEPON	Gigabit Ethernet Passive Optical Network
GFP	Generic Framing Procedure
GPON	Gigabit Passive Optical Network
GSR	GPON Service Requirements
GTC	GPON Transmission Convergence
IEEE	Institute of Electrical and Electronics Engineers
IGMP	Internet Group Management Protocol
IP	Internet Protocol
IPTV	Internet Protocol Television
ISDN	Integrated Service Digital Network
ITU-T	International Telecommunication Union
LIF	GPON Line Interface card

LLID	Logical Link Identifier
LOF	Loss of Frame
LOS	Loss of Signal
LOW	Loss of Window
MAC	Media Access Control
MDU	Multiple Dwelling Unit
MIB	Management Information Base
MoCA	Multimedia over Coax Alliance
MPCP	Multipoint Control Protocol
NG-PON	Next Generation Passive Optical Network
NSR DBA	Non Status Reporting Dynamic Bandwidth Assignment
NTT	Nippon Telegraph and Telephone
OAM	Operation, Administration, and Maintenance
ODN	Optical Data Network
OLT	Optical Line Terminal
OMCC	ONT Management and Control Channel
OMCI	ONT Management and Control Interface
ONT-ID	Optical Network Terminal Identifier
ONT/ONU	Optical Network Terminal / Optical Network Unit
OpS	Operation System
OSI	Open Systems Interconnection
P2MP	Point to Multipoint
P2P	Point to Point
PCB	Physical Control Block
PHB	Per-Hop Behavior

PIN	P-type, Intrinsic, N-type
PLI	Payload Length Indicator
PLO	Physical Layer Overhead
PLOAM	Physical Layer Operation, Administration, and Maintenance
PLS	Power Leveling Sequence
PM	Performance Monitoring
PMD	Physical Media Dependent
PON	Passive Optical Networks
POTS	Plain Old Telephone Service
PRI	Priority Field
PTI	Payload Type Indicator
P-VID	Provider VLAN Identifier
P-VLAN	Provider Virtual Local Area Network
QoS	Quality of Service
RADIUS	Remote Authentication Dial-In User Service
RF	Radio Frequency
RS	Reed-Solomon, error correction coding technique
SAR	Segmentation and Reassembly
SD	Signal Degrade
SDH	Synchronous Digital Hierarchy (ITU-T G.707 and G.708)
SER	Serialiser
SES	Severe Errors per Second
SF	Signal Fail
SFD	Start Frame Delimiter
SFU	Single Family Unit

SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
SONET	Synchronous Optical Network
SP	Strict Priority
SR DBA	Status Reporting Dynamic Bandwidth Assignment
T-CONT	Transmission Containers
TD	Traffic Descriptor
TCP	Transmission Control Protocol
TDM	Time-Division Multiplexing
TDMA	Time-Division Multiplexing Access
TOS	Type of Service
TPID	Tag Protocol Identifier
TS	Time Slot
UDP	User Datagram Protocol
US	Upstream
VBR	Variable Bit Rate
VDSL2	Very High Speed Digital Subscriber Line 2
VLAN	Virtual Local Area Network
VoD	Video on Demand
VoIP	Voice over Internet Protocol
WDM	Wavelength Division Multiplexing
WFQ	Weighted fair Queuing
WiFi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WRED	Weighted Random Early Detection

1. Introduction to Passive Optical Network

The service providers want to minimize the cost of deploying access equipment while maximizing revenue from the service offerings. This chapter will make an introduction on the dependency between services and the bandwidth that the different access networks have to offer in order to support these revenue generating services. It will also explain why the Passive Optical Networks are the most important class of fiber access systems in the world today.

1.1. Triple-play and Quad-play Services

The fact that an access network can be used to transport services other than the originally intended by the network is not new. In 1927 John Logie Baird, used a telephone line to transmit the world's first long-distance TV signal the 438 miles between London and Glasgow.

In the early 1990’s two groups of service providers - cable operators and telcos - introduced the concept of communications and entertainment bundling. The demand for Internet access from residential and business users prompted both cable and phone companies to find a way of adding data communications to the multi-channel TV and telephony services they were respectively offering.

When the cable world realized that it was in the unique technical position to offer not two, but three kinds of services by adding telephony to the mix, the term 'triple-play' was used to illustrate this new form of convergence at the network level. Cable companies, particularly in North America, are now aggressively rolling out voice services while consumers look more closely at VoIP offerings from independent broadband providers.

As the competition circles in on their high-margin voice service revenues, carriers are fighting back with new technologies and an expanded range of communication services driven by growing speeds in broadband DSL technology and improving video compression algorithms.

With both cable operators and telcos able to compete on triple-play services, it was only a matter of time until they decided to up one level and go for the latest in super-bundling: quad-play service provision. Selling multi-channel TV, fixed telephony, broadband and cellular subscriptions under one brand, with a single billing system and contact center is something that offers a number of potential benefits to both operators and subscribers. An advantage could be that the operators are being able to show advertisements over their mobile wireless operations for something that's going to happen on their video service the following day. And video content originally intended for the television, like hockey or football, can be delivered to mobile handsets on a real-time basis. Or the television can display an incoming telephone call and caller ID so the customer can decide whether or not to answer or it can be used for video conferencing.

The role of the operators is also likely to change even more in the coming years. Beyond simply operating the networks that delivers traffic to the home or business, many predict that today’s carriers will increasingly develop their own unique content that they hope consumers will be willing to pay to receive. This bundling of services is driving demand for more bandwidth in the access network.

1.2. Access Networks

Access networks fall into three categories: wireless, copper, and fiber. Wireless has the lowest deployment cost because it has the lowest outside plant costs. WiFi - IEEE 802.11b - and WiMAX - IEEE 802.16 - are the standards for wireless access and broadband access. WiMAX was designed for fixed and mobile access networks and it has a range of 5 km at a data rate of 70 Mbps. WiFi is more mature than WiMAX, but it has a range of only 100 m and a bit rate of 10 to 50 Mbps. Although both WiFi and WiMAX are relatively low cost to deploy, they lack sufficient bandwidth to support video applications because they use a point-to-multipoint architecture. Consequently, WiFi and WiMAX are useful for Web surfing applications, but impractical for higher-bandwidth and higher-revenue applications such as IPTV.

Another access technology option available to service providers is copper using digital subscriber line (DSL). Unlike wireless, DSL uses a point-to-point architecture: instead of sharing 50 Mbps over all subscribers, DSL can provide 50 Mbps or more to each subscriber. Unfortunately, DSL shares a shortcoming with wireless: it is a noise-limited access technology - the effective bandwidth DSL provides to a subscriber depends on the level of noise, which in turn depends on the length of the copper loop. DSL is capable of 100 Mbps for loop lengths less than 100 m, but can only provide less than 10 Mbps at 3000 m. If operators want to offer a compelling video service with 30 Mbps, they need to shorten loop lengths to roughly 1500 m or less, depending of the technology used. This is a viable approach, but the cost is only slightly lower than an all fiber approach and the geographic limitations of DSL technology mean not all potential subscribers can be reached (Figure 1). Also, DSL will not be able to handle the increased bandwidth demands of many new services.

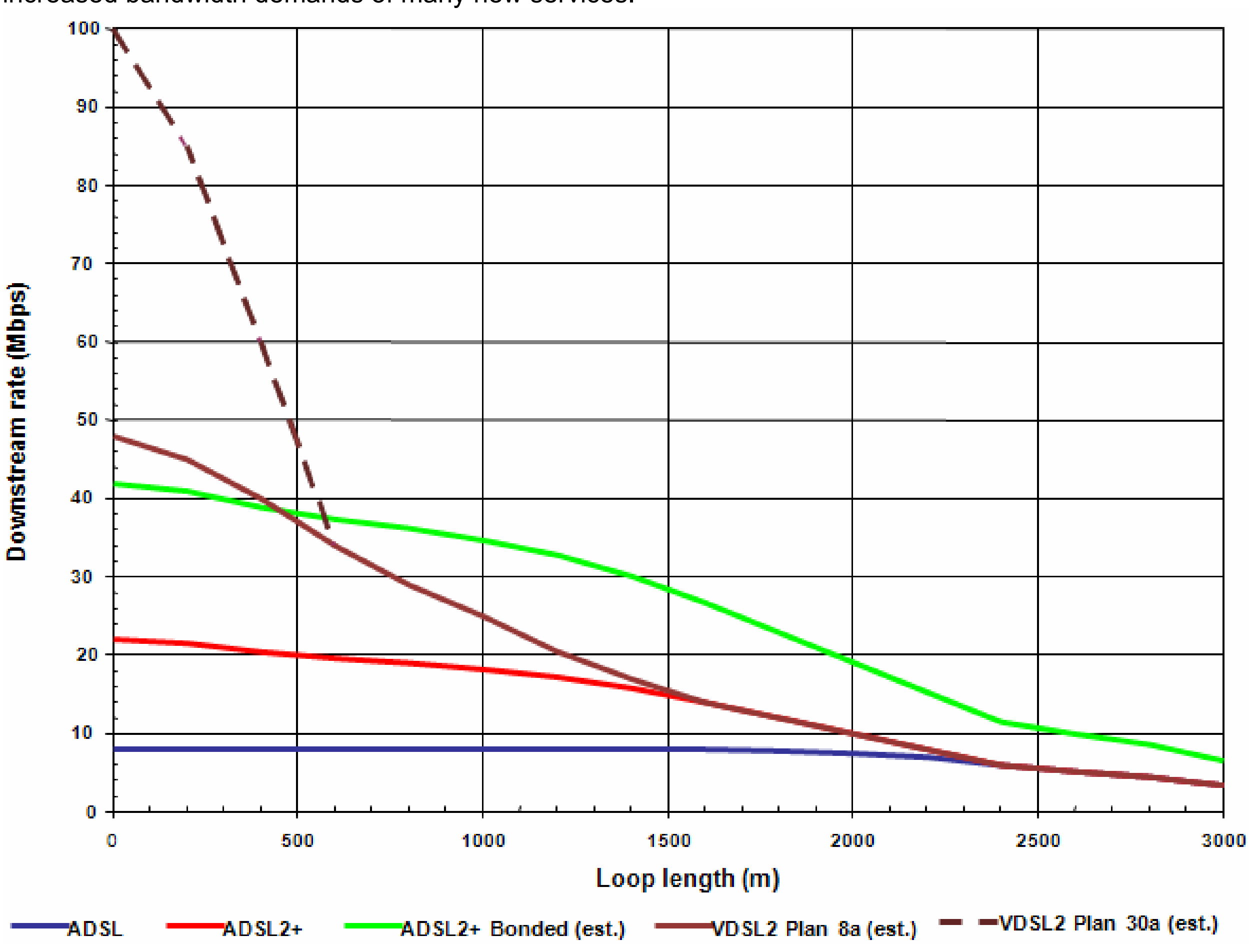


Figure 1. DSL Limitations

As an example, according to Vice Vittore (Yankee Group), service providers, at the minimum, should plan their network to support one high-definition video stream (at 8 Mbps using MPEG-4), 2 standard television video streams (3 Mbps combined), a mid-level Internet connection (3 Mbps) and voice (approximately 1 Mbps). That adds up to 15 Mbps which can be achieved with an ADSL2+ connection at the distance of approximately 1500 m from DSLAM (Digital Subscriber Line Access Multiplexer). The demand for additional high- and standard-definition video streams to support digital video recording in multiple rooms as well as higher speed Internet access for on-line gaming, e-commerce etc. and the pressure of cable companies deploying DOCSIS 3.0 - ITU-T J.222 - (Data Over Cable Service Interface Specifications) technology will require bandwidth rates of up to 50 Mbps.

DOCSIS 3.0 features management over IPv6 and channel bonding, which enables multiple downstream and upstream channels to be used together at the same time by a single subscriber.

Version	DOCSIS		EuroDOCSIS	
	Downstream	Upstream	Downstream	Upstream
1.x	42.88 (38) Mbps	10.24 (9) Mbps	55.62 (50) Mbps	10.24 (9) Mbps
2	42.88 (38) Mbps	30.72 (27) Mbps	55.62 (50) Mbps	30.72 (27) Mbps
3.0 - 4 channel	+171.52 (+152) Mbps	+122.88 (+108) Mbps	+222.48 (+200) Mbps	+122.88 (+108) Mbps
3.0 - 8 channel	+343.04 (+304) Mbps	+122.88 (+108) Mbps	+444.96 (+400) Mbps	+122.88 (+108) Mbps

Table 1. Maximum (usable) speed – shared between multiple dwellings.

Because of all these factors carriers are evaluating higher bandwidth technologies that can carry new services to a wider customer base.

1.3. Fiber Networks

As a bundling option, fiber-based access has taken the lead. Fiber is smaller in size, has better tensile strength, is immune to electrical interferences and provides the highest bandwidth and a higher degree of security because it is difficult to tap in. Fiber is just a medium – what improves the bandwidth is the optics power. Fiber-to-the-X (curb, premises, building, home) provides users with multiple phones lines, video-on-demand and high-definition television services and more.

According to Dittberner's "Broadband Shipment Analysis", 3Q 2007 FTTH (fiber-to-the-home) shipment increased 7% quarter-over-quarter on top of a strong 25% growth in 2Q 2007. Port shipments were up 38% year-over-year. Through the third quarter, 2007 shipments have exceeded 90% of the total shipments for 2006.

The increase was due to a strong showing in the North American and Japanese markets, with Korea's shipments down slightly. NTT, the dominant service provider in Japan, added about 423,000 FTTH customers. Verizon had a comparable growth, adding 227,000 FTTH customers.

However, the high cost of deployment and lack of new high-revenue services will keep, for now, FTTH from challenging DSL as the lead broadband technology. North America has not given any indication that FTTH is attractive enough to launch another initiative like Verizon's, but this may change as the cable operators begin to deploy DOCSIS 3.0 networks.

In the US demonstrating renewed confidence in its FiOS fiber-to-the-home initiative, Verizon announced in 2006 that is boosting its investment in the market to $18 billion by the year 2010, at which point expects to have 7 million customers using FiOS for Internet access.

The company sees that the FiOS services becoming profitable within four years of initial investment, which may be boosting its desire to spend more money. The $18 billion in net capital Verizon says will be invested in total from 2004 through 2010 does not include $4.9 billion that would otherwise be required to maintain traditional copper plant during the same period.

Verizon said it expects this investment to result in 7 million FiOS Internet customers and up to 4 million FiOS TV customers by year-end 2010. The migration to a fiber network will also result in $1 billion in savings in annual operating expenses by 2010. CAPEX costs are also declining while the market matures and suppliers compete for an increasing market share.

It is expected, because of the mass deployment initiatives like Verison's FiOS and AT&T's Project Lightspeed, that 100 million homes will be fibered in the next several years.

Like mentioned above the worldwide FTTX market is expected to grow substantially over the coming years with the majority of deployments using PON (Passive Optical Network) technology.

1.4. Passive Optical Networks

A fiber access network can be designed using either dedicated or shared fibers. A dedicated fiber plant, referred to as a point-to-point network, provides a dedicated fiber strand between each subscriber and the central office (CO).

In the shared fiber architecture, a single fiber from the CO serves several subscribers. This fiber is brought to a neighborhood where the signals are broken out onto separate fibers that run to the individual subscribers. Point-to-point fiber networks have a low market penetration mainly due to the additional cost it adds over a shared fiber infrastructure. Depending on the average loop length, the construction costs of outside plant based on dedicated fiber exceed those of outside plant based on shared fiber by anywhere from 20 percent to 100 percent.

In shared fiber architectures, there are two ways the signals are broken out. One method is called active Ethernet (AE), and the other is the Passive Optical Network (PON). With AE the individual signals are split out using electronic equipment near the subscriber. In the PON the signals are replicated passively by the splitter. A shared network based on a PON has several advantages over one based on AE. The outside plant of a PON incurs lower capital and operational expenditures and also has a higher reliability than AE because in the PON outside plant there are no electronic components, which are prone to failure. Lastly, perhaps one of the most crucial features of a PON-based access network is its signal rate and format transparency. Upgrading to higher bit rates is simpler for a PON than for AE. Both require upgraded electronics in the CO and customer premises, but, unlike AE, there is nothing that needs upgrading in the outside plant for a PON, as the passive splitters are agnostic to PON speed. For all these reasons, the PON is by far the most widely deployed access technology. The rate and signal format transparency became a sort of insurance policy that eased carriers into deploying PON outside plants with the understanding that an access network could flexibly be upgraded as new technologies mature or new standards evolve.

Initially, U.S. carriers built out BPON (Broadband PON) networks to the home. Today, GPON (Gigabit PON) networks are replacing these networks. In Asia, Korea Telecom is deploying EPON (Ethernet PON) networks, while in Japan NTT has announced the conversion of 30 million lines to GEPON (Gigabit Ethernet PON).

No	Description/Function	Comparison Of PON Technology		
		B-PON	E-PON / GE-PON	G-PON
1	Standardization body	ITU-T / G.983	IEEE	ITU-T / G.984
2	First draft of standardization	1995	2000	2002
3	Wavelength DS/US	1490/1310	1490/1310	1490/1310
4	DS Bit Rate	155/622/1244Mbps	1.2Gbps	1.2/2.4Gbps
5	US Bit Rate	155/622Mbps	1.2Gbps	155/622Mbps; 1.2/2.4Gbps
6	Splitting Factor	32 (64 planned)	16 / 32	32 / 64 (128 planned)
7	Bandwidth Efficiency	70%	80-90%; 50–60% for voice	93% for all types of traffic
8	Transport	ATM cells	Ethernet frames	Generic Framing Procedure (GFP)
9	3rd Wavelength - CATV/1550	Standardized	Not Standardized	Standardized
10	Fiber protection	Standardized	None	Standardized
11	Downstream security	Churning/AES	None	Standardized (AES)
12	FEC	None	Standardized	Standardized (RS)

Table 2. PON standards comparison

With its very high bandwidth PON is the ideal solution. The passive nature of the connection means that only simple, non-powered equipment is used to split the light signal from the Central Office to the user.

PON networks can be used in conjunction with other gear in the network. One of the possible configurations can use PON equipment to provide the backbone for an expanded DSL network. In this configuration, PON extends the reach of the DSL and brings it closer to the customer, allowing IPTV and VoD services to be deployed over existing copper connections to the home.

The network itself consists of a distribution cable routed from the CO to the subscriber neighborhood. In the vicinity of the subscriber the optical fiber is connected to a passive optical splitter. Here the optical signal is divided into a number of identical signals. These signals that are routed to individual subscribers using fiber optic drop cables. Optical signals from the subscriber to the CO travel in the reverse path.

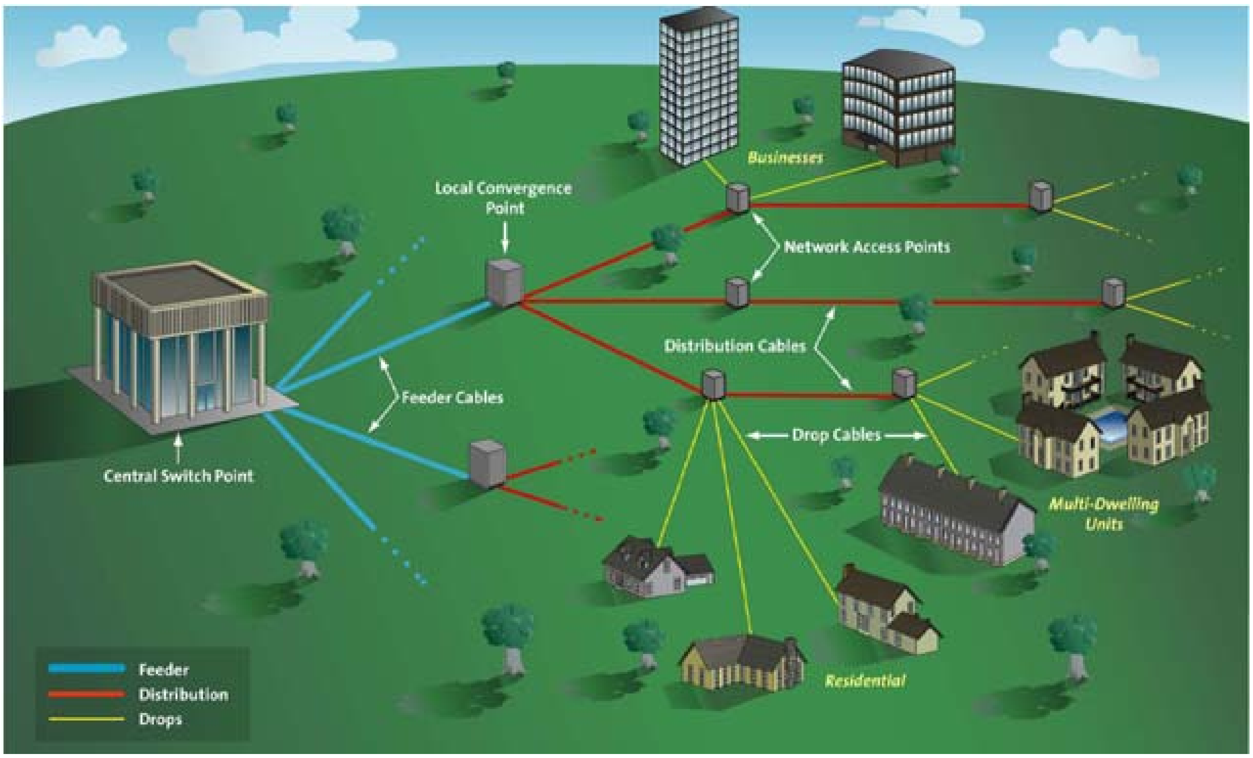


Figure 2. High level view of PON deployment.

The network elements used in PON are fibers, splitters and connectors and they are passive. The optical path consisting of these passive elements is called Optical Data Network (ODN). The passive optical splitter has a single input and multiple outputs. Typically the number of outputs is 2n (i.e. 2, 4, 8, etc) and the optical power is split evenly between outputs. An optical splitter is a bi-directional device. Not only do optical signals travel from the input to the outputs, they can also traverse from the outputs to the input fiber. When an optical signal is inserted into one of the splitter outputs the signal will reappear on the single input. In a properly manufactured splitter there is no cross talk between output ports.

The link connecting the CO and the optical splitter is known as a feeder cable. The distribution cables originate at the optical splitter. From there they either connect directly to the users or run in a multiple fiber cable to network access points from where the individual drop cables are connected to the customer premises.

The communication path from the CO to the subscriber is referred to as the downstream signal. The communication path from the subscriber to the CO is referred to as the upstream signal. In most PON applications the downstream and upstream optical signals are carried over the same fiber. The wavelengths of these two signals can be the same or different. 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. In fact all of the international PON standards (see above) specify 1490 nm for the downstream wavelength and 1310 nm for the upstream wavelength. The 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 in the CO have a 1490 laser and a 1310 receiver. Diplexers used at the subscriber premises have a 1310 laser and a 1490 receiver.

In addition to the downstream and upstream baseband signals, a PON can also carry a broadband overlay on a third wavelength. This wavelength overlay is typically used to transport broadcast downstream CATV at 1550 nm. Unlike the baseband signal, this broadband overlay is an analog signal, even if it contains analog data, digital data, or both.

1.5. PON Link Power Budget.

Downstream optical signal is divided between N separate paths by the optical splitter. If a splitter is designed to divide the incident optical power evenly, and if P is the optical power entering the splitter, the power level going to each subscriber is P/N [3].This is the maximum allowed difference in optical power level between the optical transmitter output and the minimum receiver sensitivity needed to establish a specified BER (Bit Error Rate):

BER = N_e / N_t, where:

- N_e is number of errors,
- N_t is total number of bits.

Typically error rates for fiber range from 10^{-9} to 10^{-15}.

Because there are three wavelengths involved 1310, 1490 and 1550, when calculating optical power budget one should have to calculate optical power budget for these wavelengths separately. The main reasons for doing this are:

- Fiber attenuation varies with wavelength (see Figure 4),
- Receiver sensitivities are different in upstream and downstream directions.

If ‘P_s’ is the optical power from source and if ‘P_r’ is the minimum receiver sensitivity needed for a specific BER, then:

$P_t = P_s - P_r$ = n x connector loss + α L + N x splice loss + splitter loss + WDM coupler loss + system margin, where:

- n is number of connectors,
- α is fiber attenuation in dB/Km,
- L is fiber length.

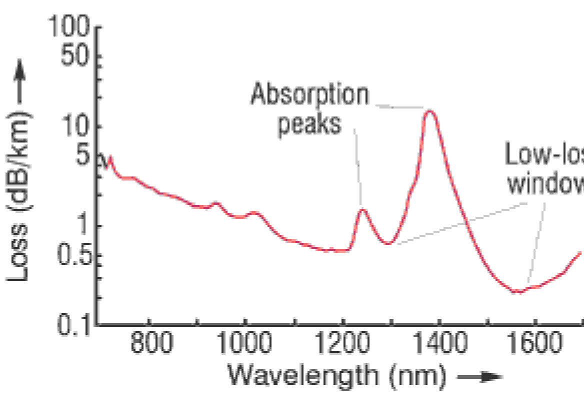


Figure 3. Attenuation at different wavelengths

The minimum and maximum loss an optical signal may experience between OLT and ONT or backward direction is specified. See Table 2 for class A, B and C ODN minimum - maximum path loss:

Class of Laser	Type	Optical Budget
A	Fabry-Perot	5 – 20 dB
B	Fabry-Perot	10 – 25 dB
B+	Fabry-Perot	13 – 28 dB
C	Distributed Feedback Laser	15 – 30 dB

Table 3. PON Optical budget

Included in this attenuation ranges are losses resulting from:

- optical fiber - for single mode 0.35 db/km at 1300 nm, 0.25 db/km at 1550 nm;
- splices – 0.05 to 0.1 for fusion and 0.5 for mechanical;
- connectors – SC insertion loss 0.3db, LC insertion loss 0.1 db;
- optical splitters – see Table 4.

In addition, the link designer needs to take into consideration the possible occurrences of other link degradation such as additional splices and fiber lengths resulting from cable repairs, the effects of environmental factors, and unforeseen degradation in any passive components.

Optical Splitting Ratio	Splitter Loss	Distance per Opical Class		
		Class A	Class B	Class C
1:16	14 dB	13 km	33 km	52 km
1:32	17 dB	2 km	22 km	42 km
1:64	20 dB	0 km	11 km	31 km

Table 4. Longest PON Transmission distance under ideal conditions

1.6. PON Architecture

The PON has a unique architectural feature: in the downstream direction the PON behaves as a point-to-multipoint network and in the upstream the PON behaves as a point-to-point network. Because of this, separate PON protocols have been developed to accommodate this unique feature. Before discussing details of the different international standards governing PONs, it is helpful to discuss the basic functions that a PON protocol performs.

Any discussion of PON protocols involves two standard acronyms that identify the CO equipment and the subscriber equipment. These are the OLT for Optical Line Terminal as CO equipment and the ONT / ONU for Optical Network Terminal / Optical Network Unit as subscriber equipment. These terms have the same meaning, but ONU is an IEEE terminology and ONT is an ITU-T terminology.

The OLT contains a specially designed burst-mode receiver because the amplitude and phase of information packets arriving from different locations can vary widely from packet to packet. The lasers at the ONT must be turned off when they are not transmitting.

Because the downstream is a point-to-multipoint network, PON protocols necessarily employ a master/slave architecture where the OLT is the master and the ONTs are slaves.

The OLT controls the bidirectional flow of information across the ODN. In the downstream the function of an OLT is to take in the voice, data, and video traffic from a long-haul or metro-network (usually through an aggregator) and broadcast to all ONTs on the ODN. In the upstream an OLT accepts and distributes multiple types of traffic from the customers. A typical OLT is designed to control more than one PON.

The ONT is providing an optical connection to the PON on the upstream side and is interfacing the user equipment on the other side. Depending of the requirements of the customer or block of users the ONT supports a mix of services including Ethernet rates, T1 or E1 (1.544 Mbps or 2.048 Mbps) and

DS3 or E3 (44.736 Mbps or 34.368 Mbps), telephone connections, ATM interfaces (155 Mbps), and digital and analog video formats. The function of the ONT is to aggregate and transport various type of information traffic coming from the users and sends it upstream over a single fiber PON infrastructure.

ONT is usually housed in an outdoor equipment shelter and it has to have a local power source and an emergency battery backup. The link to the customer premises can be a twisted pair copper wire, a coaxial cable, an optical fiber link, or a wireless connection.

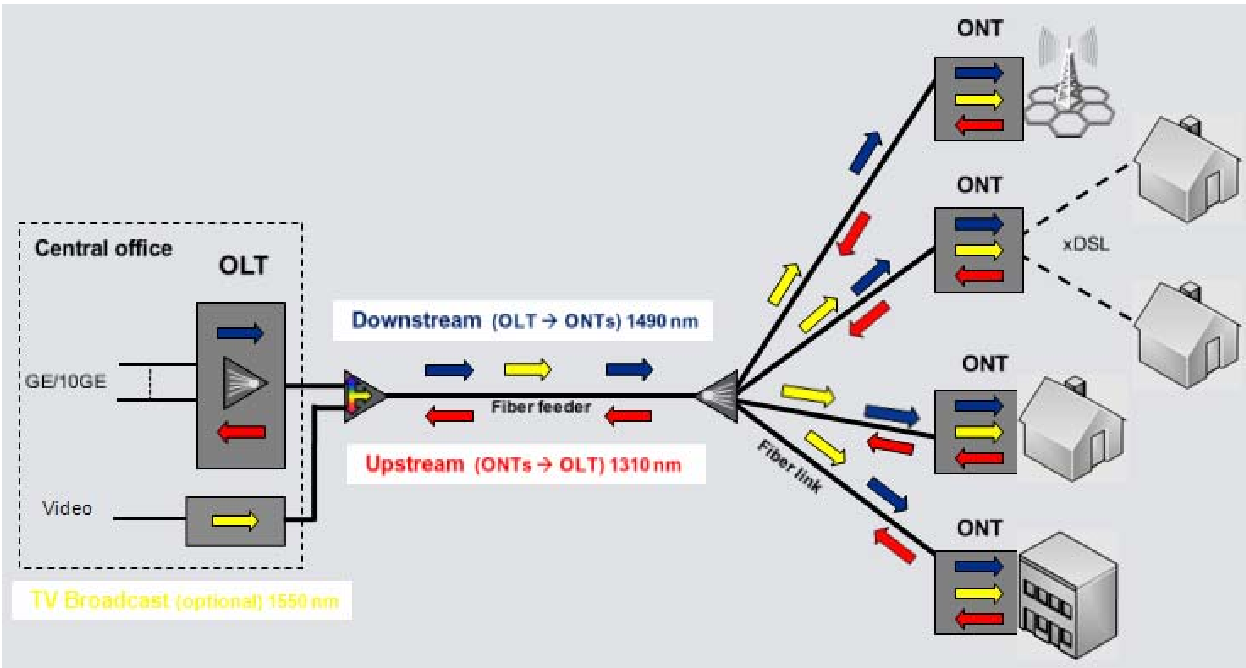


Figure 4. PON architecture

In this architectural framework the OLT performs three fundamental functions:

1. Handles all the OAM&P for the ONTs;
2. Controls and coordinates all upstream transmissions by the ONTs;
3. When sending downstream data, the OLT must label each packet with the ID of the intended recipient.

The OAM&P consists of admitting new ONTs to the PON and provisioning services. It also includes the function of ranging. Ranging is the process whereby the optical delay between the OLT and a given ONT is determined. The optical delay is different for each ONT because the physical length of fiber is different for each.

Time-Division Multiplexing (TDM) is used by OLT to combine incoming voice and data streams that are destined for PON customers (Figure 6). The independent information streams coming into OLT are interleaved into a single information steam by the OLT and the signal is broadcasted to all ONTs in that PON. Each ONT discards or accepts the incoming packets depending on the packet header addressing. Encryption can be implemented to maintain privacy since the downstream signal is broadcasted and every ONT receives all the information destined for each terminal.

Since up to 64 ONTs use the same wavelength and share a common optical fiber the Time-Division Multiple Access (TDMA) is used so each user transmits information within a specific time slot (TS) at a prearranged data rate (Figure 7). This is inefficient since many TSs will be empty when several network users do not have information to be sent back to the CO. A more efficient process is Dynamic Bandwidth Allocation (DBA) with which TSs of an idle or low utilization user are assigned to a more active customer. There are various DBA schemes that can be implemented through an OLT in a particular network and depends of factors as user priorities, the quality of service guaranteed to specific customers, the desired response time for bandwidth allocation, the bandwidth requested by user, etc.

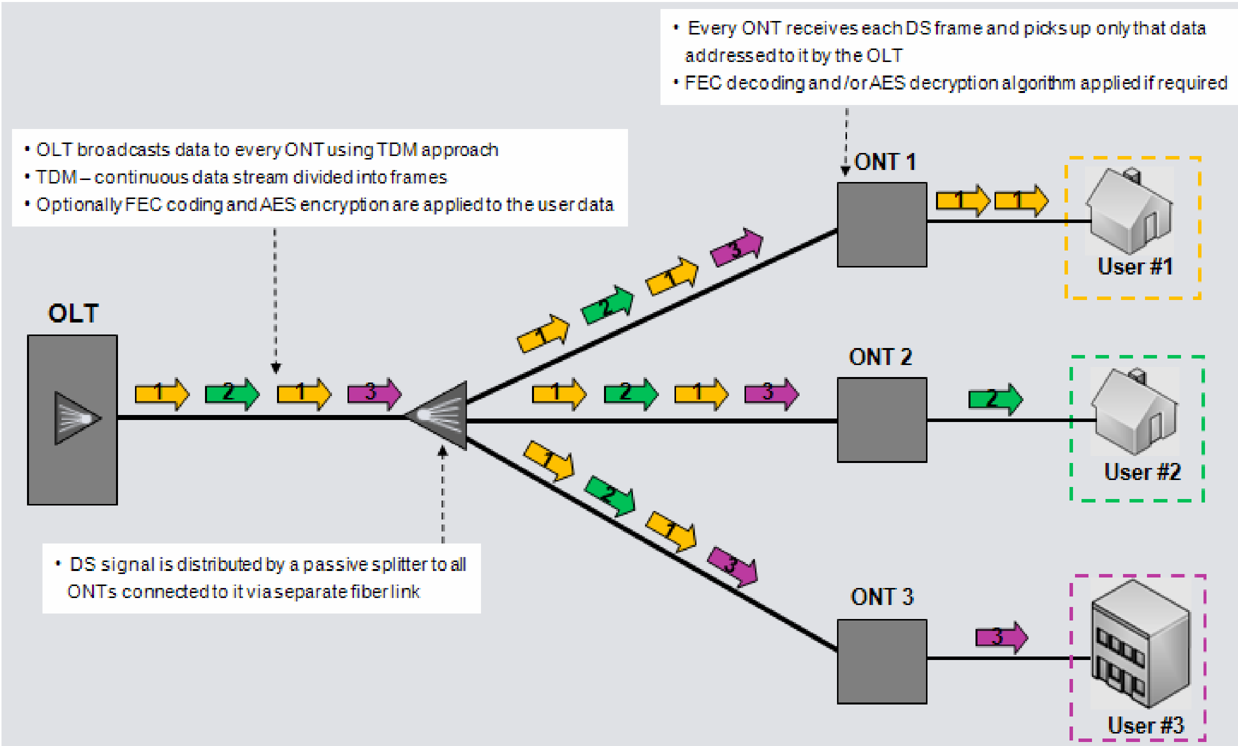


Figure 5. Downstream Data Transmission

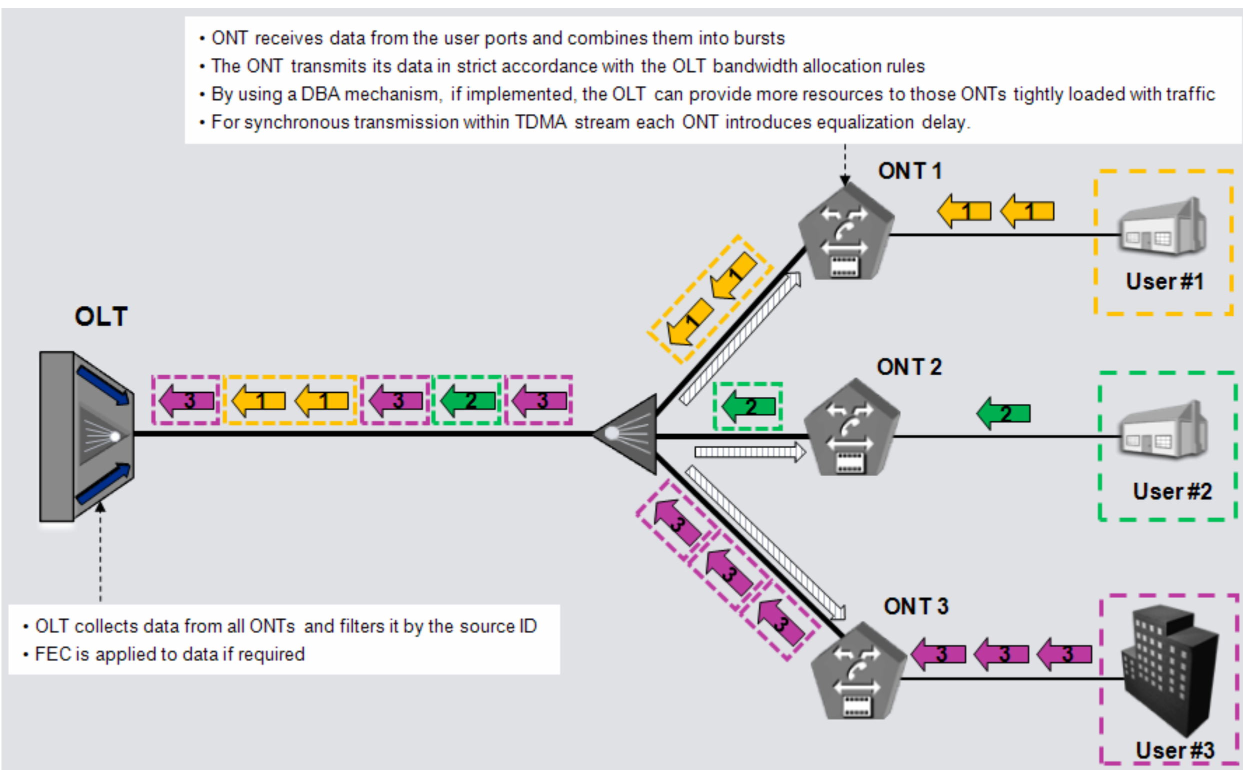


Figure 6. Upstream Data Transmission

2. Passive Optical Network Standards

A PON may be operated under a variety of different transmission standards, such as a BPON (Broadband Passive Optical Network), EPON (Ethernet Passive Optical Network) and GPON (Gigabit Passive Optical Network). Each standard has different transmission bandwidths and transmission speeds and it may include different media access control (MAC) information and operation, administration and management (OAM) information encoding schemes. This chapter will introduce the BPON and EPON standards. GPON will be described in detail in the next chapter.

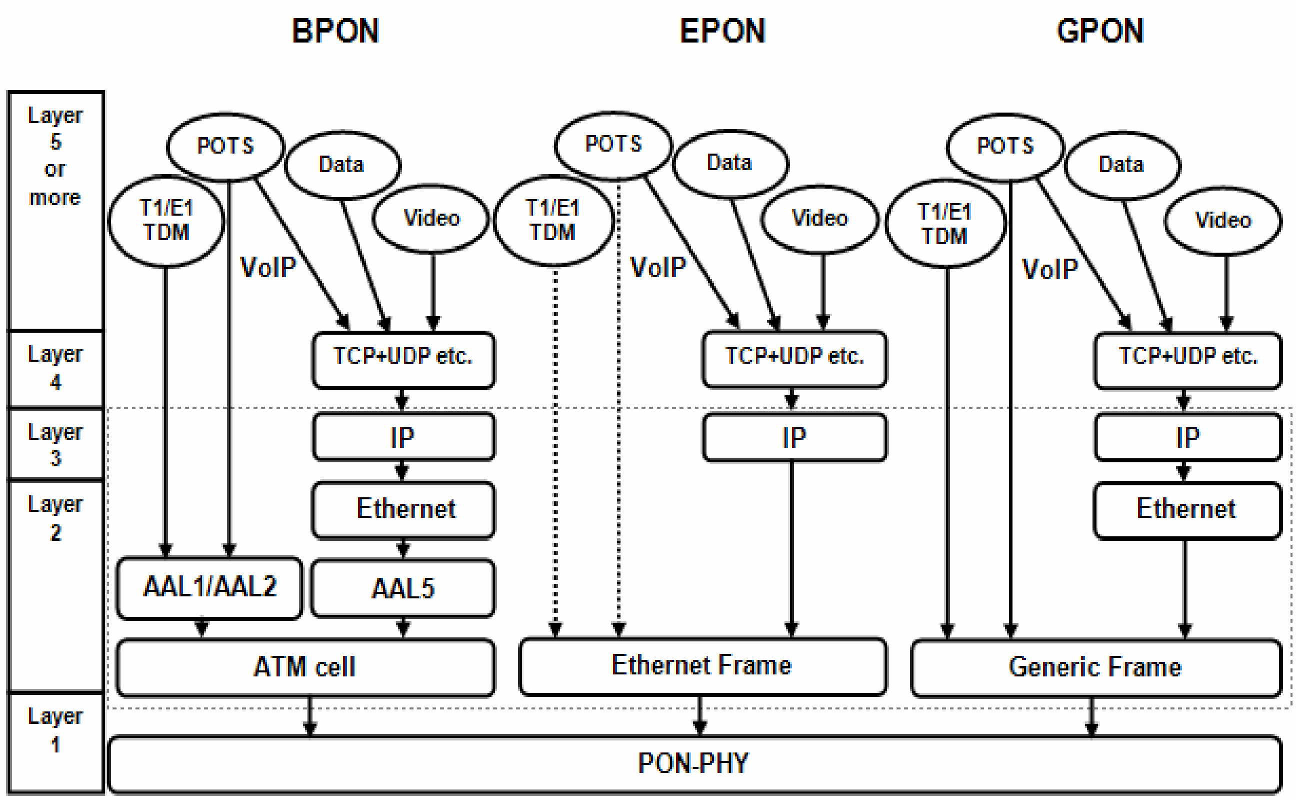


Figure 7. The layered structure of different PON standards.

2.1. BPON Standard

BPON is the ITU-T standard specified in ITU-T G.983.x recommendations and it was first ratified in October 1998. Since it was a first attempt at a PON standard it has 2 major weaknesses: is establishing ATM (Asynchronous Transfer Mode) as the sole underlying transport mechanism and has an optical performance criteria that is difficult to meet at higher bandwidths.

The ATM cells are 53 bytes long packets that contain 48 bytes of information and have 5 bytes of overhead. The use of ATM allows different QoS parameters for real time traffic, but on the other hand the use of ATM added complexity to BPON. As shown in Figure 5 all kind of traffic first need to be encapsulated in ATM cells.

The ATM Adaptation Layer (AAL) relays ATM cells between ATM Layer and higher layer. When relaying information received from the higher layers, it segments the data into ATM cells. When relaying information received from the ATM Layer, it must reassemble the payloads into a format the higher layers can understand. This operation, which is called Segmentation and Reassembly (SAR), is the main task of

AAL. Different AALs were defined in supporting different traffic or service expected to be used. The service classes and the corresponding types of AALs were as follows:

- Class A - Constant Bit Rate (CBR) service: AAL1 supports a connection-oriented service in which the bit rate is constant. Examples of this service include 64 Kbit/sec voice, fixed-rate uncompressed video and leased lines for private data networks.
- Class B - Variable Bit Rate (VBR) service: AAL2 supports a connection-oriented service in which the bit rate is variable but requires a bounded delay for delivery. Examples of this service include compressed packetized voice or video. The requirement on bounded delay for delivery is necessary for the receiver to reconstruct the original uncompressed voice or video.
- Class C - Connection-oriented data service: For connection-oriented file transfer and in general, data network applications where a connection is set up before data is transferred, this type of service has variable bit rate and does not require bounded delay for delivery. Two AAL protocols were defined to support this service class, and have been merged into a single type, called AAL3/4. But with its high complexity, the AAL5 protocol is often used to support this class of service.

Initially, because BPON protocol allowed only ATM transport using baseband signaling it was designated APON for ATM PON. In February 2001, when the 1550 nm overlay was added with G.983.3, the name was changed to BPON for Broadband PON.

Like DSL, APON/BPON was developed at a time when ATM we expected to surpass IP/Ethernet as the dominant protocol - history has shown that not to be the case. Although ATM is a proven technology with scalable and flexible traffic management capabilities and robust QoS features it does have several limitations:

- 10% cell tax overhead.
- Single corrupt or dropped ATM cell requires retransmission of the entire IP packet even though other ATM cells belonging to the same IP packet may be received correctly. This results in a large bandwidth overhead and a high demand of processing resources.

In conclusion the fundamental reliance of BPON on ATM has turned out to be an unnecessary burden to support and has made the migration of BPON-based systems from ATM to all-IP a problematic proposition.

The optical requirements established by BPON have also proven to be problematic. During normal operation of a PON, each ONT turns on its laser, transmits a short burst of data and then shuts its laser off. This is referred to as burst mode operation. Because the ONTs are at different distances and optical loss points on the PON, the upstream receiver in the OLT must accommodate a considerable range of optical powers and clock phases as the different ONTs burst on and off. In order for the OLT to adjust to these changes during clock and data recovery, the ONTs send a series of ones and zeros before sending valid data. The length of this one-zero pattern is called the Burst Overhead Time. For BPON this burst overhead time was specified at 3 bytes (4 bits guard time and 20 bit preamble + delimiter). There are two upstream data rates specified in the BPON recommendation: 155 & 622 Mbps. While the 3-byte overhead is adequate to perform clock and data recovery at 155 Mbps it is not adequate at 622 Mbps and higher. Considerable effort has been spent studying ways to relax the 3-byte overhead at higher data rates but no consensus has ever emerged. Given that the ITU now has a next-generation PON protocol that replaces it, BPON will only ever be a 155 Mbps upstream protocol.

Although ITU-T G.983.x recommendations are directed at BPON the GPON standard (ITU-T G.984.x) draws heavily on it in order to promote backward compatibility with existing ODNs that complies with 983.x recommendations.

- G.983.1 – Broadband optical access systems based on PON.

This recommendation describes a flexible access network that can support the bandwidth requirements of ISDN (Integrated Services Digital Network) – 64 kbps to 2 Mbps - and B-ISDN (Broadband ISDN) – up to 622.08 Mbps – services. It addresses symmetrical and asymmetrical systems with nominal downstream upstream rates of up to 1244.16 Mbps and upstream rates of up to 622.08 Mbps. It proposes specifications for the physical media dependent (PMD) layer, the transmission control (TC) layer, the process for detection and registration of an ONT, and the ONT ranging protocol.

- G983.2 – ONT management and control interface specifications for BPON.

This recommendation gives the requirements for managing ONTs through the OLT using the ONT management and control interface (OMCI). It specifies the managed entities of a protocol independent management information base (MIB) that describes the information exchange procedure between OLT and ONT, and it covers the ONT management and control messages.

- G983.3 – A broadband optical access system with increased service capability by wavelength allocation.

This recommendation defines the requirements for a new wavelength allocation to distribute APON and additional service signals such as video broadcast distribution. Detailed specifications of these services, such as modulation schemes and signal format are not covered.

- G983.4 – A broadband optical access system with increased service capability using dynamic bandwidth assignment.

This recommendation specifies the requirements for adding DBA functionality. It gives the specifications for DBA operation and for DBA related communication between OLT and ONTs.

- G983.5 – A broadband optical access system with enhanced survivability.

This recommendation extends ITU-T G983.1 to include BPON survivability architectures, protection performance criteria, and protection switching criteria and protocols for delivering highly reliable services.

2.2. EPON Standard

In November 2000, a group of Ethernet vendors started their own standardization effort, under the auspices of the Institute of Electrical and Electronics Engineers (IEEE), through the formation of the Ethernet in the First Mile (EFM) study group. The group was to extend Ethernet into the subscriber access area. Ethernet over point-to-multipoint fiber (also known as EPON) became one of the focus areas of this group, along with Ethernet over copper. The EFM task force completed its charter in June 2004, culminating in ratification of IEEE 802.3ah.

Transport mechanism for EPON is Ethernet but it doesn't support all features available in 802.3x Ethernet. The access network packet length is restricted and carrier sense multiple access / collision detection protocol CSMA/CD) is not supported. As shown in Figure 8 EPON does not support TDM (POTS, T1/E1) services and only support voice using VoIP.

EPON's rapid adoption was driven by the early decision to define the physical layer specification using relatively minor modifications to inexpensive high-volume 1 Gbps optical components. This has greatly reduced optics cost to levels comparable to those of continuous mode optics.

While in the IEEE 802.3ah standard EPON link budget was conservatively specified as 24 dB with minimum 1:16 split ratio, in practice the transceiver technology has matured enough so that components providing 29 dB power budget became commercially available, resulting in most EPON-based networks being deployed with a 1:32 split ratio, with some as high as 1:64.

EPON traffic uses the same Ethernet packet format, with standard inter packet gap (IPG), as found in any enterprise switch. EPON also uses the same media access control (MAC) found in any IEEE 802.3 compliant device.

7 bytes	1 byte	6 bytes	6 bytes	2 bytes	46-1500 bytes	4 bytes
Preamble	**SFD**	**MAC Dest.**	**MAC Source**	**Length**	**PDU / Pad**	**FCS**

Figure 8. IEEE 802.3 frame – 72 to 1526 bytes long

Since the EPON frame has the same size and format as the standard Ethernet frame (Figure 6) – it does not use encapsulating framing in either the upstream or downstream direction. A modification is made in the content of the Ethernet preamble and start frame delimiter (SFD), which together account for 8 bytes, as follows:

- 1 byte for the start of packet delimiter which contains clocking information. This synchronization marker is sent every 2 ms to synchronize the ONTs with the OLT;
- 3 bytes reserved for future use;
- 2 byte tag called logical link identifier (LLID) that defines the destination ONT;
- 2 byte frame check sequence (FCS) that validates the preamble integrity.

In the downstream the LLID field defines the destination ONT. The ONT receives and filters the received frames based on the LLID in the frame preamble and its unique LLID value assigned by the OLT. A special value is reserved for broadcast messages sent to all ONTs. In the upstream the source ONT places its assigned LLID in the frame. This LLID exists only in the EPON itself, since the ONT strips this field prior to sending the packet to the customer. Most ONT equipment registers as a single ONT and uses a single LLID for data transport but some equipment may register as multiple virtual ONTs, thereby establishing multiple LLIDs. The OLT grants each virtual ONT separately, including repeated allocation of the optical overhead. The OLT maintains a separate management channel to each virtual ONT, and has to also identify the service level agreement (SLA) for each virtual ONT.

The point to multipoint connectivity is supported by the multipoint control protocol (MPCP), which uses standard Ethernet packets generated in the MAC sub layer. The MPCP arbitrates the channel access between OLT and ONTs. Some functions that MPCP performs include auto-discovery, ONT registration, ranging, bandwidth polling. Another function is to assign the upstream bandwidth dynamically to various customers. The MPCP described in 802.3ah does not specify any particular DBA algorithm.

An ONT is discovered and registered to the EPON with a uniquely assigned LLID by the OLT using an MPCP handshake. The following process, which takes less than 1 second, is performed using special types of 64 bytes control messages:

- Using discovery GATE messages the OLT sends a request to all unregistered ONTs to transmit;
- An unregistered ONT answers by using a REGISTER_REQUEST message;
- When received and approved, the OLT registers the ONT using the REGISTER message;
- The handshake ends with the ONT acknowledgment REGISTER_ACK.

During steady state operation, the OLT controls the ONTs transmission window with GATE messages. The ONT uses the REPORT messages to indicate its bandwidth requirements. This is done in the form of queue occupancies since each ONT has a set of buffers which hold queued Ethernet frames that are ready for upstream transmission. A REPORT message from an ONT can indicate the status of 8 queues with each queue having multiple thresholds. Then the OLT calculates the ONT transmission window length using DBA. Once the DBA completes the upstream scheduling the OLT uses the GATE messages to issue transmission grants – up to 4 per message – to the ONTs. The transmission grant also specifies the transmission start time and the transmission length for an ONT.

For the ONT to transmit in a specific TS it needs to be synchronized with the OLT and the other ONTs. The PON clock is a 16 ns resolution counter that is carried in all MPCP messages. The ONT uses the received timestamp to lock to the OLT time base. The OLT uses returned timestamps to measure ONT round-trip delay and schedule collision-free upstream transmissions.

EPON uses a frame-based FEC mechanism based on the RS (255,239) algorithm. Each frame is encoded separately, and all per-frame parity bytes are added at the end of the frame. This approach allows ONTs without FEC capabilities to receive FEC-encoded frames, ignoring the appended parity data. FEC can be selectively activated per ONT.

Although not defined in the IEEE 802.3ah specification, all EPON implementations incorporate encryption.

OAM functionality is another important EPON breakthrough. OAM is established after the discovery process and is maintained by periodic message transmission. Information about remote failures is conveyed using flags in OAM messages to indicate failure status. The remote ONT can be instructed to return incoming packets as part of the remote loopback functionality.

Link monitoring, where any Ethernet variable of the remote port can be retrieved by the OLT, is the most useful EPON OAM function. OAM link information can be extended beyond the OLT by placing a simple network management protocol (SNMP) agent at the OLT.

OAM includes vendor extension mechanisms to provide a convenient and lightweight method to manage the additional functionality, which can lead to differing OAM variants as carriers customize their products.

A significant EPON enhancement to run at higher speed has begun. This enhancement would provide a significant capacity increase for TDM PON systems. The IEEE has formed the 802.3av task force to consider the definition of 10G-EPON that operates at 10 Gbps downstream and 1 or 10 Gbps upstream (exp. 2009).

3. GPON Standard

The growing demand for higher speeds and the wide use of ATM and Ethernet were the main reason behind the idea of developing a PON with capabilities beyond those of BPON and EPON. In order for such a PON to transmit efficiently variable length packets at gigabit per second rates a new type a frame format had to be developed. The Full Service Access Network (FSAN) group started such an effort in April 2001. In January 2003 the first two standards were approved by the ITU-T, covering the requirements and basic architecture (G.984.1), and the physical-medium-dependent (PMD) layer (G.984.2). In February 2004 G.984.3 specifying the G-PON transmission convergence (TC) layer was ratified, followed by G.984.4, which standardizes the G-PON management requirements. Since then, a few amendments have reached consent by the ITU-T on most of the documents in the series.

3.1. GPON General Characteristics

ITU-T G.984.1 – Gigabit-capable Passive Optical Networks (GPON): General characteristics - describes the network architecture, types of services, supported bit rates, logical and physical reach, optical power splitting ratio, protection mechanisms and security requirements (Table 5).

Parameter	GSR Specifications
Service	Full service: 10/100 Mbps Ethernet, SONET/SDH, ATM, POTS
Access rate	Downstream: 1.244 and 2.488 Gbps
	Upstream: 155 Mbps, 622 Mbps, 1.244 Gbps, 2.488 Gbps
Distance	10 or 20 Km
Splitting Number	Maximum of 64
Wavelengths	Downstream voice/data: 1480 to 1500 nm
	Upstream voice/data: 1260 to 1360 nm
	Downstream video: 1550 to 1560 nm
Protection Switching	Fully redundant 1+1 protection
	Partially redundant 1:N protection
Security	Information security at the protocol level for downstream traffic

Table 5. Summary of GPON Service Requirements

Ref: FTTX Concepts and applications by Gerd Keiser

In order to insure backward compatibility with BPON the recommendation maintains some requirements of the ITU-T G.983.1. This allows several different types of redundancy of links and equipment for network protection such as fully redundant 1+1 protection and partially redundant 1:N protection.

In a 1+1 protection the traffic is transmitted simultaneously over two separate fiber paths from the source to the destination. Because usually these paths do not overlap at any point, a fiber cut would only affect one transmission link. The receiving site will select one of the links as the working fiber for the reception of data. In case that the fiber on that link is cut or the transmission on that links fails, the receiver will switch to the protection fiber and will continue to receive data. This protection method provides rapid switchover during failures and does not require a protection signaling protocol between the source and the destination. The downfall of this protection scheme is that requires duplicate fibers and redundant transmission equipment for each link.

The 1:N protection mechanism offers a more economical use of fibers and equipment. In order to achieve this, one protection fiber is shared among N working fibers. This arrangement will then offer protection in the case that one of the working fibers fails. For most operational networks this level of protection is adequate since failures of multiple fibers are rare – that is if not all fibers are in the same cable. In contrast to the 1+1 protection scheme, the 1:N protection mechanism uses only the working fiber for transmission during the normal operation. When there is a failure on a particular link, the source and the destination both will switch over to the protection fiber. This mechanism requires an automatic switching protocol between the endpoints to enable the use of the protection link.

The GPON network architecture follows that of a the standard PON concept and as such it supports a two-wavelength WDM scheme for downstream and upstream digital services (see Figure 4). Additionally, another downstream wavelength can be used for distribution of analog video service. The network supports up to 60 km reach, with 20 km differential reach between ONTs (Figure 7). The split ratio supported by the standard is up to 128. Practical deployments typically would have lower reach and split ratio, limited by the optical budget.

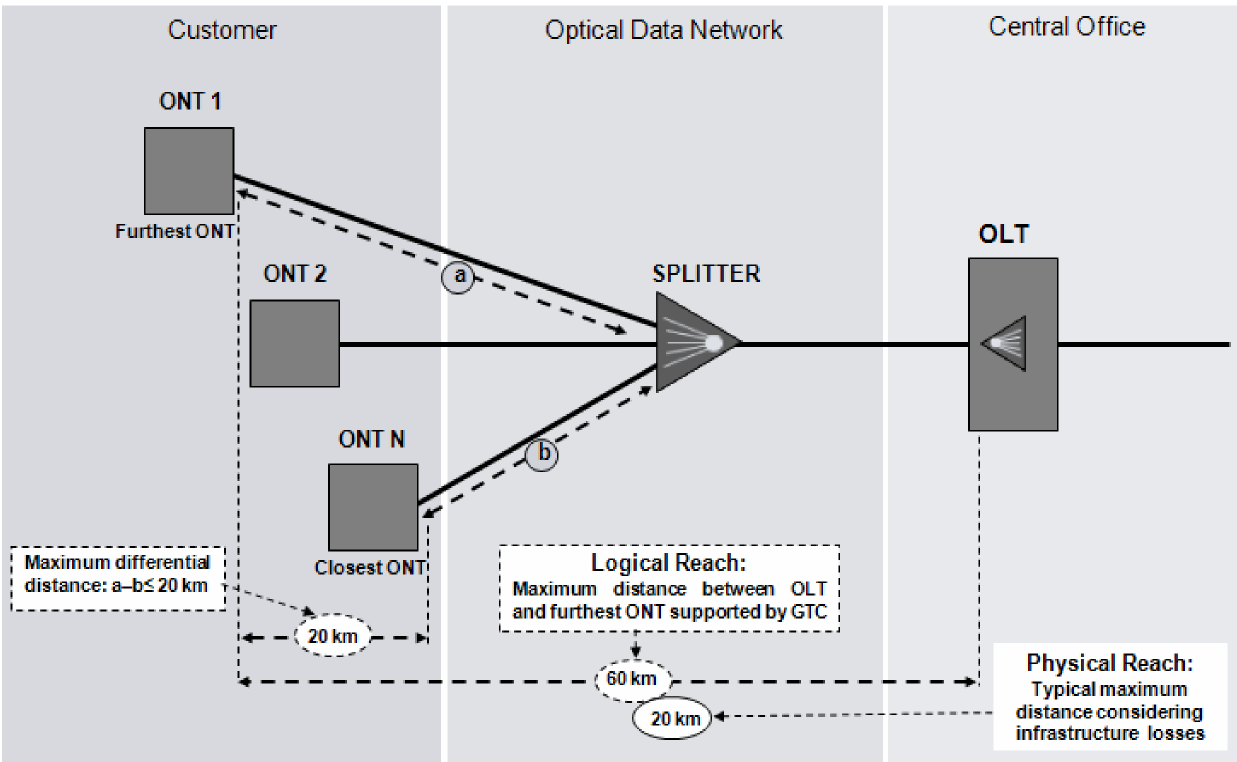


Figure 9. GPON Maximum reach

3.2. PMD Layer

ITU-T G.984.2 – Gigabit-capable Passive Optical Networks (GPON): Physical Media Dependent (PMD) layer specification – describes the requirements of the PMD layer for GPON, covering the range of GPON upstream and downstream bit rates, and the optical parameters for the various rate combinations. As network operators requirements evolved, the preferred GPON bit rate was selected to be 2.488 Gbps downstream and 1.244 Gbps upstream.

This focus has then allowed the definition of best practice optical parameters for GPON, which was documented as an amendment to G.984.2. The parameters, known as Class B+, apply to a network with or without a video overlay and to ONTs based on either APD or PIN technology.

3.2.1. Burst Mode Transmission

Part of G.984.2 is the specification of the burst mode parameters. Even though GPON is a synchronous network in which the OLT lets the ONTs know when they can transmit, this process has a timing uncertainty. This is more of a factor in GPON than in BPON and EPON because of the higher data rates and therefore the smaller pulse widths in a packet burst.

Because the uplink signals are transmitted in burst mode the operational characteristics of an OLT optical receiver differ from a conventional one. The reason for this is that the amplitude and phase of packets received from different user locations can vary from packet to packet. Figure 8 shows conventional point-to-point link. There is no variation in logic 1s received. Figure 9 shows the pattern of signals which may arrive at OLT receiver. In this case the signal amplitude changes from packet to packet depending upon how far is the ONT from OLT. If the closet and farthest ONTs attached to a common optical splitter are 10 km apart and if the fiber attenuation is 0.5 db/Km, there is a 5 dB difference in the signal amplitudes that arrive at OLT from these two ONTs – this is the case if both have the same upstream laser output level. Amplitude variation only happens in upstream direction at OLT and not at ONT.

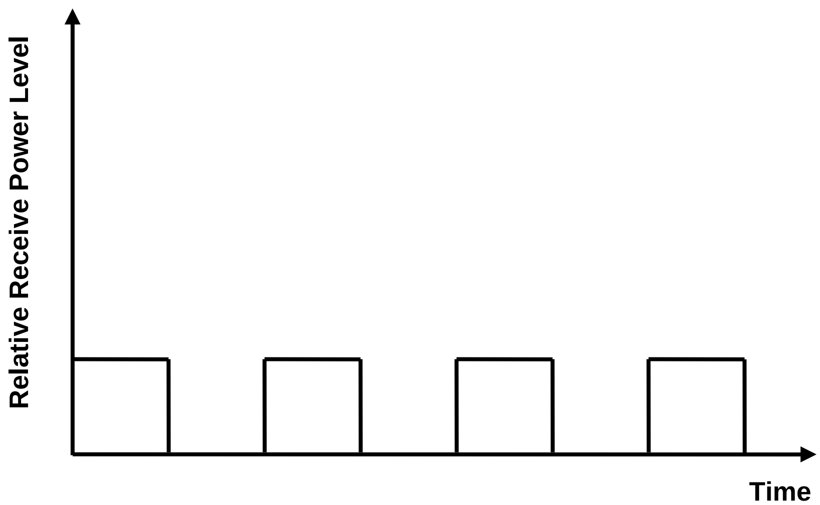


Figure 11. Received packets in a P2P link

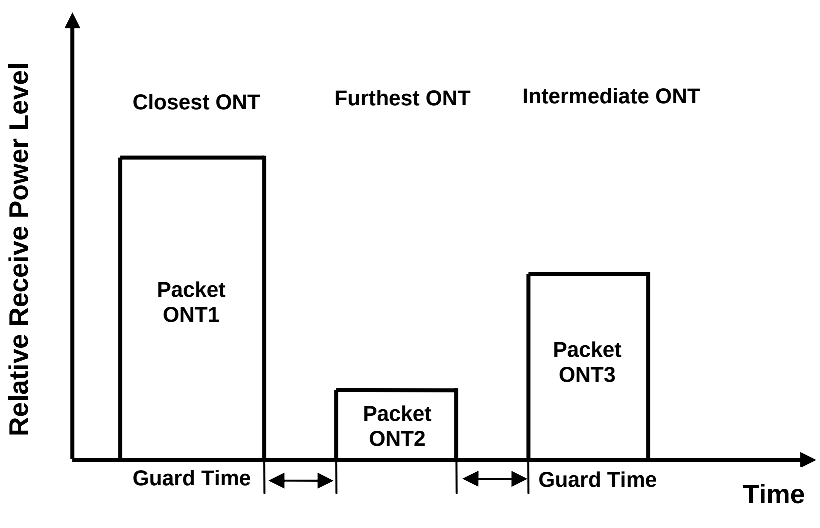


Figure 11. Received packets at OLT

In order to avoid interference with transmissions of other ONTs the laser must be turned off when an ONT is not transmitting. As more ONTs are connected to the OLT, the GPON becomes more complex and the result will be a very fast variation in the amplitudes of the incoming packets which can lead to packets collision. Because of this a guard time is needed between successive packets from ONTs. The guard time nominally is 25.6 ns, which means that the number of bits allocated to that field becomes larger as the data rate increases: 25.6 ns guard time consumes 16 bits at 622 Mbps, 32 bits at 1244 Mbps and 64 bits at 2488 Mbps.

3.2.2. PMD Building Blocks and Optical Power Control

The next figure depicts the GPON physical layer as a set of PMD building blocks. The 1.25-Gb/s upstream transmitter (US-TX) mainly contains the burst-mode laser diode driver (BM-LDD), while the upstream receiver (US-RX) comprises the avalanche photodiode/Trans-impedance amplifier (APD-TIA) and the burst mode receiver (BM-RX). The BM-CPA (Burst Mode Clock and Phase Alignment) belongs to OLT. On ONT side a serialiser (SER) is used to serialise the traffic at low speeds (155 Mbps or 77 Mbps) coming from network terminal towards US-TX. On OLT side a deserialiser (DES) is used to deserialise the traffic from US-RX towards Line Terminal (LT).

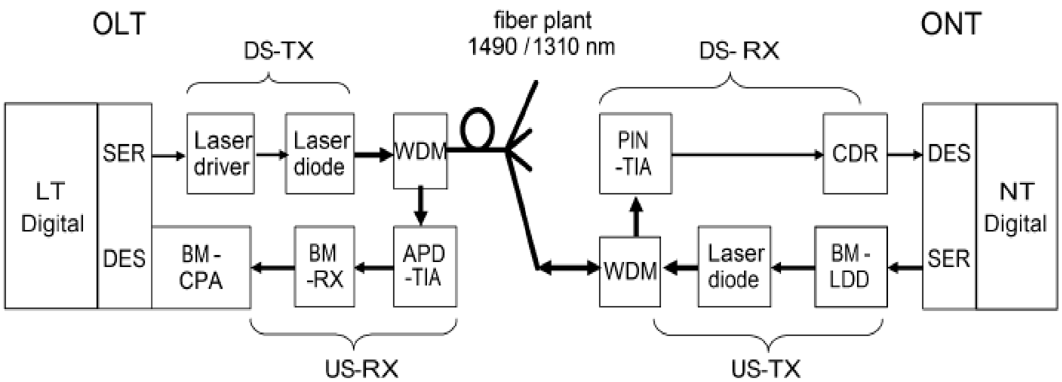


Figure 12. GPON Physical Media Dependant (PMD) building blocks.

For high efficiency and to avoid time overlap between incoming burst, it is required that US-TX should be turned on and off very quickly. The worst case scenario is if at the US-RX a strong burst is followed by a weak one. In this case if the strong US-TX is not turned off fast enough than its residual power will disturb the preamble of the weak burst.

If an ONT is located close to OLT, then the US-RX might see a relatively high optical power from that ONT. The signal corresponding to a digital 0 of a strong burst can even be larger than the signal level of digital 1 of a weak burst. To address this problem G.984.2 allows for optical power control in the ONT transmitter through the implementation of three power level modes. Mean launched Min and Max are described in G.984.2 and these values correspond to Mode 0. The values corresponding to Mode 1 and Mode 2 are respectively 3 dB and 6 dB lower. For example, a class B ONT for 1244 Mbps with power leveling capability will have to comply with following output power ranges:

Mode	Min Power (dBm)	Max Power (dBm)
Mode 0	-2 dBm	+3 dBm
Mode 1	-5 dBm	0 dBm
Mode 2	-8 dBm	-3 dBm

Table 6. ONT power leveling modesClock and Phase Recovery

Another important aspect in PON is the clocking mechanism; GPON has the same clock extraction capabilities as described in BPON recommendation G983.1. The clock of upstream signal is recovered by the ONT from the downstream signal; this means that the frequency of local system upstream clock will be exactly same as the frequency of clock at the OLT. Therefore the clock recovery circuit in the OLT BM-RX does not need to recover the upstream clock frequency from the received signal.

The clock phase of received burst, coming from different ONTs is unpredictable due to the difference in the physical location and therefore different optical paths. The CPA circuit in BM-RX must perform a fast acquisition of the phase of the incoming signal at the start of each burst.

G.984.2 states that there should be 72 consecutive Identical Digits (CID) in the transmitted bit stream. This means that the CPA should accurately remember its phase during at least 72 consecutive identical digits.

3.3. GTC Layer

The GPON TC (GTC) layer specified by G.984.3 - Gigabit-capable Passive Optical Networks (GPON): Transmission convergence layer specification - performs the adaptation of customer data onto the PMD layer. Not only that, but the GTC layer also provides basic management of the GPON network.

This layer is equivalent with layer 2 – data transmission layer – of the OSI reference model. The GTC layer defines two adaptation methods for data transport: asynchronous transfer mode (ATM) and GPON-encapsulation-method (GEM). GEM format is based on a slightly modified version of the ITU-T G.7041 – Generic frame procedure (GFP) – which gives the specifications for sending IP packets over SONET/SDH networks. Because GEM has become the preferred method, ATM will not be discussed here. GTC with GEM allows for low overhead adaptation of various protocols, including Ethernet and SONET/SDH.

GTC also provides the MAC function, coordinating the interleaving of upstream transmissions from multiple ONTs. The control functions of GTC consist of a protocol and procedures for registering ONTs to the GPON network, and monitoring their health of transport features such as forward error correction (FEC), encryption, and bandwidth allocation.

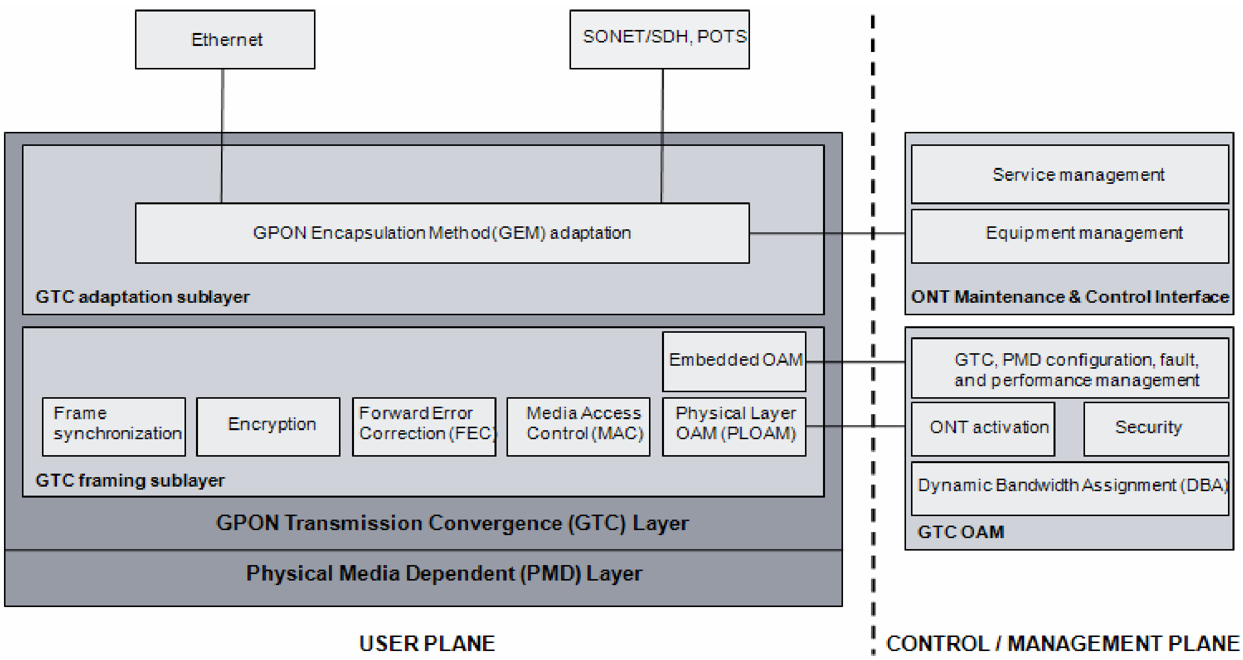


Figure 13. GPON layers

As seen in Figure 11 the GTC layer is divided into two sublayers:

1. The lower framing sublayer defines the GTC frame structure, which is asymmetrical, carrying different overhead information downstream and upstream;
2. The higher sublayer of GTC is the GTC adaptation sublayer based on GEM. GEM defines a protocol-independent connection-oriented encapsulation for variable-size packets

3.3.1. GTC Framing Sublayer

The GTC uses a 125 μs downstream frame, and it transports an 8 kHz signal that provides a reference clock to the ONTs. The upstream frame comprises a sequence of transmissions from ONTs as dictated by the OLT. GTC framing in both directions it is “rate agnostic”: different G-PON rates have the same frame structure and vary only in the amount of payload.

3.3.1.1. Downstream GPON Frame Format

The downstream GTC frame consists of Physical Control Block (PCBd) - a header containing all overhead fields - and payload consisting of ATM and GEM segments.

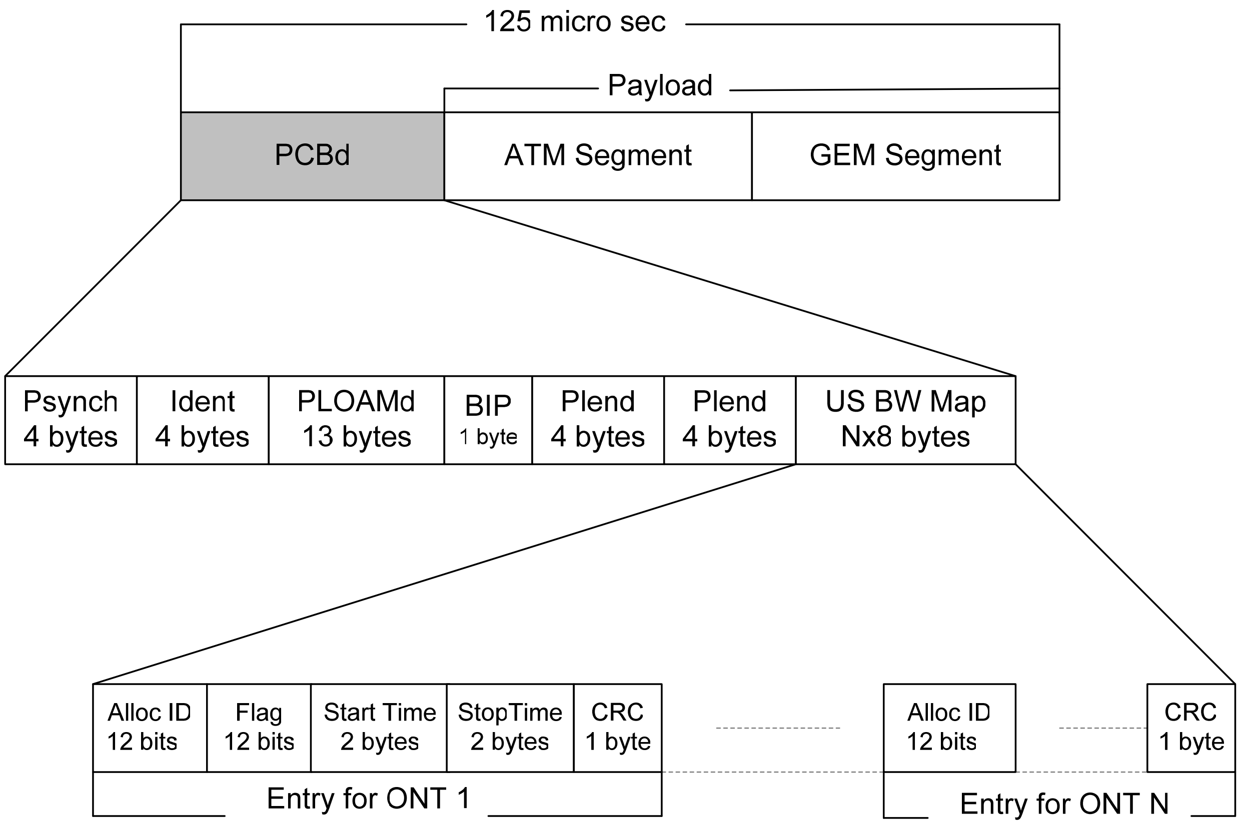


Figure 14. Downstream GPON Frame

The PCBd includes framing related fields, and the physical layer operations, administration, and maintenance (PLOAM) field which handles functions such as alarms or threshold crossing alerts. The PLOAMd carries a message-based protocol for PMD and GTC layer management.

The PCBd also includes the bandwidth map field specifying the ONTs upstream transmission allocation. The US BW map contains N entries associated with N TSs allocation identification for the ONTs.

Detail of PCBd:

- Psynch - 4 byte frame synchronization field. The ONT uses this field to find the beginning of the frame. Once the ONT is synchronized can begin to process the PCBd information.
- Ident - 4 byte segment that contains an 8 KHz counter, FEC status bit (downstream), an encryption key switch over bit and 8 status bits (for future use). It is used to indicate larger frame structure. The most significant 1 bit indicates if FEC is used.

- PLOAMd - 13 byte physical layer operation and management message. See PLOAMu for details.
- BIP - 1 byte bit interleaved parity field. The receiver will also compute the bit interleaved parity and compare its result to the BIP transmitted in order to measure the number of errors on the link.
- Plend – 4 byte downstream payload indicator which gives the length of US BW map and the size of the ATM segment. It is sent twice for redundancy and error robustness. The length of the bandwidth map is given by the first 12 bits. This limits the number of Alloc IDs that may be granted in any 125 μs time duration to 4095. The last 8 bits are used by CRC.
- US BW Map – Nx8 bytes for N transmission TSs, with the following structure:
  - Alloc ID – 12 bit allocation identifier assigned to an ONT,
  - Flag – 12 bits that allow the upstream transmission of physical layer overhead blocks for a designated ONT,
  - Start Time – 2 byte start pointer that indicates when the upstream transmission window starts; time measured in bytes with the beginning of the upstream GTC frame designated as time 0,
  - Stop Time – 2 byte stop pointer that indicates when the upstream transmission window stops,
  - CRC – 1 byte CRC that provides 2 bit error detection and 1 bit error correction of the bandwidth allocation field.

The difference between Stop time of an ONT and Start time of the next ONT represents the guard time for the upstream transmission.

3.3.1.2. Upstream GPON Frame Format

The upstream traffic consists of successive transmissions from ONTs in a particular sequence of frames based on the transmission TS allocations developed by the OLT. In order to have a proper reception a certain amount of burst overhead is needed at the start of an ONT upstream transmission. Figure 13 shows the format of an upstream frame, consisting of four types of PON overhead fields and variable length payload.

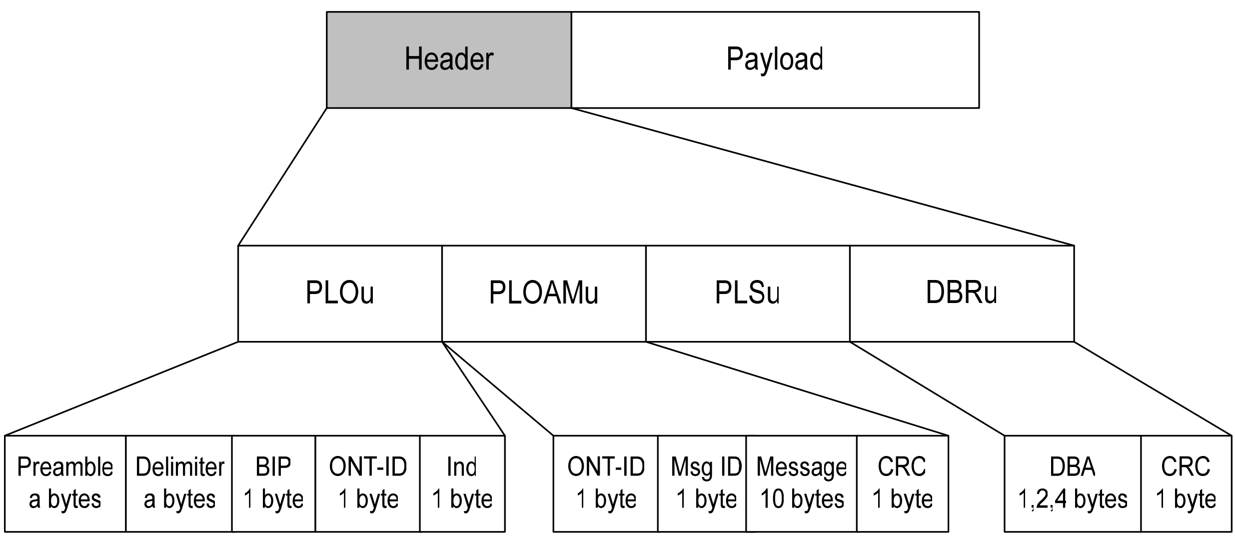


Figure 15. Upstream GPON Frame

Every upstream frame contains PLOu but the use of PLOAMu, PLSu and DBRu are optional depending upon the downstream flags in the US BW map.

Upstream frame header fields:

- PLOu - physical layer overhead heads each ONT transmission and ensures the proper physical layer operation of the burst mode upstream link. It contains a preamble and a delimiter configurable by the OLT and 3 fields that correspond to an ONT as a whole:
  - BIP - bit interleaved parity,

- ONT-ID – the unique ID of the ONT that is sending this transmission. It is assigned to the ONT during the ranging procedure. The OLT can check this field against its allocation records to check if the correct ONT is transmitting,
- Ind - indication field that provides real time ONT status report to the OLT.

- PLOAMu - physical layer operation, administration and management. It is used for management functions like ranging of an ONT, alarm notification. This field is protected by CRC.
  - Msg ID – type of message,
  - Message – payload for the GTC message.
- PLSu - power leveling sequence is a 120 bytes field that contains information regarding laser power levels at the ONT. The OLT uses PLSu to adjust the optical power level on ONT. This power control mechanism is used for initial power set-up or to change he power mode of the ONT transmitter. The former only happens during ONT activation procedures, while the latter can occur during operation as well as during activation. As a result the PLSu can be requested at all times and has to be transmitted regardless of the need to perform transmitter adjustment;
- DBRu - dynamic bandwidth report informs the OLT about the queue length of each Alloc ID at ONT. This field is protected by CRC. To maintain delineation the ONT must transmit the appropriate length DBA field even if the DBA mode is not supported.

Every time an ONT takes over the PON medium from another ONT, it must send a new copy of the PLOu data. If an ONT is given two Alloc IDs that are contiguous (the Stop Time of one is 1 less than the Start Time of the other), then the ONT will suppress sending the PLOu data for the second Alloc ID. This suppression can reoccur for as many contiguous Alloc IDs the ONT is granted by the OLT. The requirement for contiguous allocations forbids the OLT from leaving gaps between same ONT transmissions. The allocations must either be exactly contiguous, or they must be scheduled as if they are coming from two different ONTs.

Following any of these overhead transmissions, the user payload data is sent until the location indicated by the Stop Time pointer.

3.3.2. GTC Adaptation Sublayer

The higher sublayer of GTC is the TC adaptation sublayer based on GEM. GEM defines a protocol-independent connection-oriented encapsulation for variable-size packets. If the encapsulation payload is more than 1500 bytes long it will be fragmented into smaller packets and the destination equipment is responsible for reassembling the fragments.

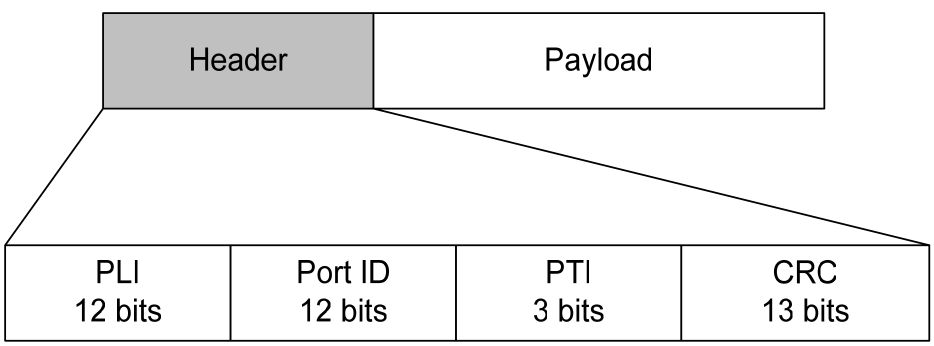


Figure 16. GEM Frame

GEM frames include a 5-byte header:

- PLI – payload length indicator gives the length of the GEM payload.
- Port ID – port identification number that tells to which service flow this fragment belongs.
- PTI – payload type indicator specifies if the fragment is the end of a user datagram, if the traffic is congested, or if the GEM payload contains OAM information.
- CRC – CRC for header control.

In the downstream, frames are transmitted from the OLT to the ONTs using the GEM payload partition. The OLT may allocate as much duration as it needs in the downstream, up to and including nearly all the downstream frame. The ONT framing sublayer filters the incoming frames based on Port ID, and delivers the appropriate frames to the ONT GEM client.

In the upstream, frames are transmitted from the ONT to the OLT using the configured GEM allocation time. The ONT buffers GEM frames as they arrive, and then sends them in bursts in the allocated time to do so by the OLT. The OLT receives the frames, multiplexes them with bursts from other ONTs, passing them all to the OLT GEM client.

Since GEM frames may be fragmented a client packet may span multiple GEM frames.

GEM's virtual connection unit is called GEM port – identified by Port ID - and can contain a flow to/from a physical or logical port of an ONT. GEM ports are bundled onto transmission containers (T-CONTs).

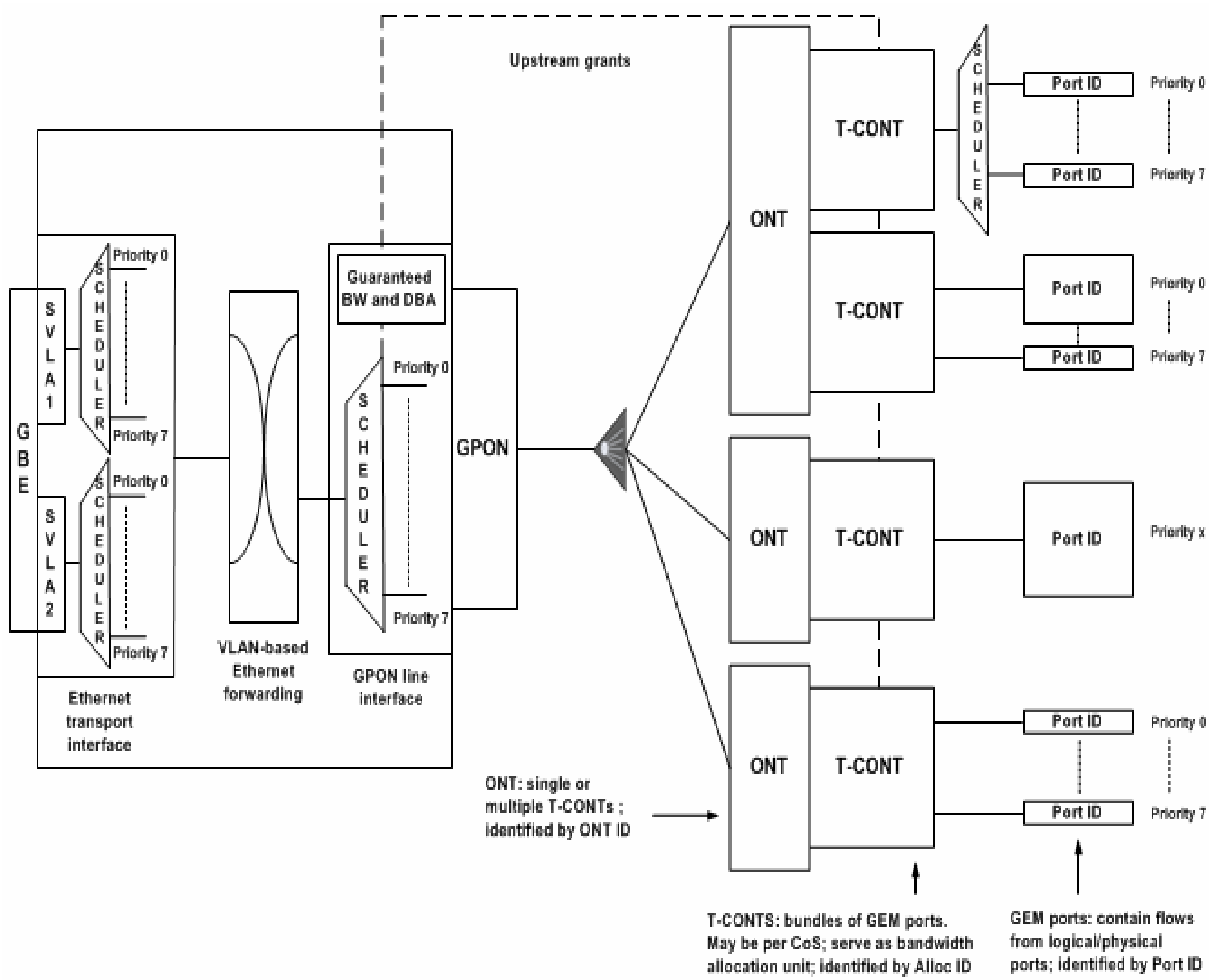


Figure 17. Multiplexing Architecture and Traffic Management

3.3.3. Transmission containers

Ethernet is the delivery mechanism for a converged access network delivering IP services. As a result, Ethernet has evolved to include service-delivery technology that supports the various class of service (CoS) requirements for voice, video, and data. IEEE 802.1p was developed to establish service priority levels and 802.1q was devised to support VLAN tagging for establishing specified transmission links within an Ethernet network for those services.

However, the Layer 2 (Ethernet) and Layer 3 (IP) CoS mechanisms will only be as good as the QoS of the transport is. If the transport is subject to latency and jitter, so will the services be no matter how they are prioritized. For TDMA PON, the upstream QoS capabilities become the issue when all of the ONTs on the PON compete for upstream capacity and priority in a TDMA fashion.

T-CONTs are a PON-layer mechanism for upstream QoS whereby services of the same CoS type as determined by Layer 2 or Layer 3 methods use the same T-CONT type. Thus, voice services will be assigned to a voice T-CONT by the ONT and best-effort data will be assigned to best-effort T-CONTs. DBA ensures that T-CONTs with a higher CoS, such as voice, get priority access on the PON and preempt lower-CoS T-CONTs, such as Internet data.

Characteristics of T-CONTs:

- Can carry ATM and/or GEM traffic with various classes of services; report their buffer status to the OLT.
- Is dynamically receiving grants from OLT that are identified by Alloc ID.
- It can accommodate one or more physical queues and aggregates them into a single logical buffer.
- It is a transport entity in the TC layer that transfers higher-layer information transparently from input to output.
- Information traversing a T-CONT is unchanged except where degradation occurs in the transfer process.
- A data grant is associated with one and only one T-CONT. T-CONTs physically occur in the ONT hardware and software.

In the upstream direction the BW to be used by an ONT depends on the traffic scenario at that ONT and on the traffic pattern at the others ONTs in the PON. Because of the shared medium the OLT is informed about the BW demand at each ONT and based on this information it grants access to the ONTs at fixed TSs in the downstream frame. For the upstream traffic the frame can be considered to be divided into different containers types.

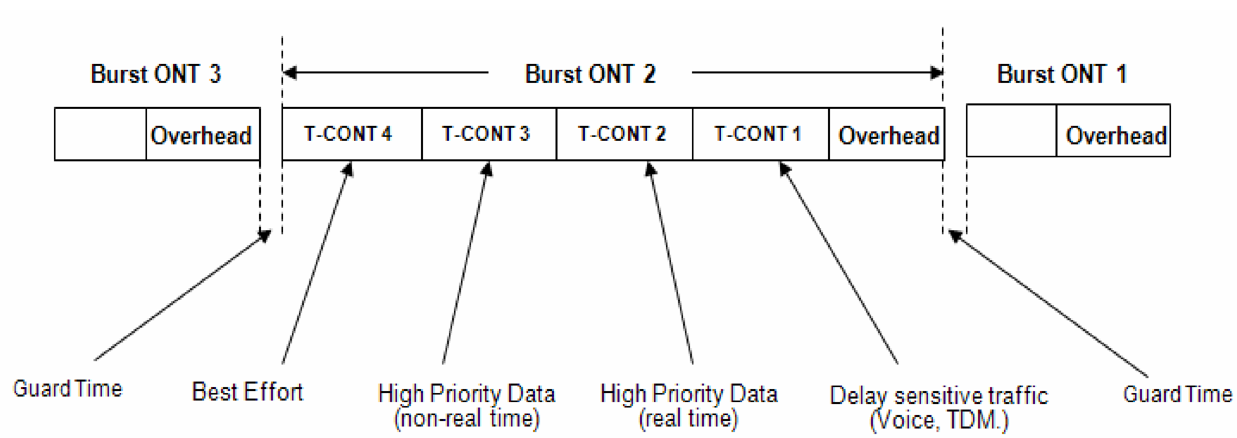


Figure 18. Upstream Traffic

Each T-CONT has bandwidth-related parameters associated with it that are used in the grant assignment process. Four categories of bandwidth are identified for DBA – fixed, assured, non-assured, and best-effort (listed from highest to lowest priority in terms of granting). Five T-CONT types are defined with different combinations of these bandwidth categories. Each ONT can support one or more T-CONTs;

the specific T-CONT type or combination of T-CONT types on a given ONT is tailored to support the QoS requirements of the traffic flows on the ONT. For example, T-CONT type 5 is the most flexible type, accommodating all four bandwidth categories, and a single type 5 T-CONT on an ONT can be used to accommodate multiple traffic flows with a variety of QoS. There are 5 types of T-CONTs:

T-CONT TYPE	DELAY SENSITIVE	FIXED BW	ASSURED BW	NON-ASSURED BW	BEST EFFORT BW	SUBJECT OF DBA
T-CONT 1	yes	Allocated Static				no
T-CONT 2	no		Allocated Dynamic			yes
T-CONT 3	no		Allocated Dynamic	Allocated Dynamic		yes
T-CONT 4	no				Allocated Dynamic	yes
T-CONT 5	no	Allocated Static	Allocated Dynamic	Allocated Dynamic	Allocated Dynamic	yes

Table 7. T-CONT Types

The T-CONT arrangement is configurable by the OLT; however, the most use is a single T-CONT per ONT, or multiple T-CONTs, one per service class, per ONT. Because the T-CONTs are identified by the 12 bits of the Alloc ID there are a maximum of 4095 T-CONTs per GPON. In GEM, the T-CONT block length is negotiated by G-PON OMCI, and the default is 48 bytes.

3.3.4. Dynamic Bandwidth Assignment

DBA is the process through which the ONTs (and their associated T-CONTs) dynamically request upstream bandwidth (either implicitly or explicitly). Using traffic monitoring at OLT or buffer status reporting from ONTs to OLT, the OLT reassigns the ONTs upstream bandwidth accordingly.

As per ITU-T G.984.3 the following DBA functionalities are performed in every T-CONT:

1. Detection of congestion status by OLT and/or ONU;
2. Report of congestion status to OLT;
3. Update of assigned bandwidth by OLT according to provisioned parameters;
4. Issues of grants by OLT according to updated bandwidth and T-CONT types;
5. Management issues for DBA operations.

Because some of the DBA reporting functions are optional a handshaking procedure between the OLT and ONTs is necessary at the startup time. The GPON OMCI channel is used to negotiate the type of DBA reports that will be used.

Until the OMCI handshake is completed, the DBA features cannot be used. Regardless of its DBA capabilities the transport system is made to be fault-tolerant by setting requirements for the ONT to always produce the correct format of report requested by the OLT,.

Two methods of DBA are defined for G-PON: status-reporting DBA, which is based on ONT reports via the DBRu field, and non-status-reporting DBA, which is based on OLT monitoring per T-CONT utilization.

3.3.4.1. Non-Status Reporting DBA

All OLTs should provide traffic monitoring, so when there are ONTs that do not report their status they can still obtain some basic DBA functionality. NSR DBA invokes bandwidth assignment which does not need report from ONT. However, it provides dynamic assignment by using traffic monitoring by OLT itself.

OLT recognizes congestion status of each T-CONT by self-monitoring the incoming traffic flows. In this mode, the DBA field in DBRu will never be sent, as the OLT should never request it. In the exceptional situation where the OLT does request the DBRu, the ONT must send it, although its contents will be ignored by the OLT.

In NSR DBA, the OLT continuously allocates a small amount of extra bandwidth to each ONT. If the ONT has no traffic to send, it transmits idle frames during its excess allocation. Such idle frames indicate that the buffer of the T-CONT is empty at the moment and the number of data grants assigned to it can be properly reduced. The extra data grants are then assigned to other T-CONTs which do not send idle cells. By this the bandwidth allocation to those ONTs is increased. Once the ONT's burst has been transferred, the OLT observes a large number of idle frames from the given ONT, and reduces its allocation accordingly.

Since in NSR DBA the entire DBA mechanism is contained within the OLT there is no protocol features required. NSR DBA has the advantage that it imposes no requirements on the ONT, and the disadvantage that there is no way for the OLT to know how best to assign bandwidth across several ONTs that need more.

3.3.4.2. Status Reporting DBA

In SR DBA method, at the request of the OLT, a T-CONT reports its packet buffer length as its traffic status. A given ONT may have several T-CONTs, each with its own priority or traffic class. The ONT reports each T-CONT separately to the OLT. Once the traffic status of the T-CONT is obtained, the OLT can then reapportion the data grants accordingly.

There are three mechanisms for signaling DBA reports over the G-PON: status indications in the PLOu, piggyback reports in the DBRu, and ONT report in the DBA payload. Because the other DBA methods are deprecated, ITU-T G.984.3 strongly recommends the implementation of piggyback reports. Piggyback reports provide a continuous update of the traffic status of a specific T-CONT.

The piggyback DBA report consists of a 1-, 2-, or 4-byte message that specifies the amount of data waiting in the T-CONT buffer corresponding to the Alloc ID that triggered the DBRu transmission. The OLT triggers the transmission of the DBRu by setting the appropriate code point in the flags field of the bandwidth map allocation structure. The report is then covered by the CRC-8 that is part of the DBRu.

If the OLT does not want to permit transmission of upstream data to a T-CONT, OLT can assign time for only DBRu. However, even if OLT receives the report, it does not always apply this report to bandwidth update. On the other hand, if a T-CONT cannot report the number of blocks which are stored in its buffer for some reason, it responds with an invalid code in the DBA field to OLT. The transmission of the DBA field is mandatory if the OLT requests it, because if the DBA field is missing, the format of upstream data cannot be recognized.

Comparing with NSR DBA this method fares better in rapid reconciliation of traffic congestion, but carries a price due to its complex protocol and associated overhead. The two methods may be used simultaneously to meet the dynamic traffic needs of different services, as recommended by the ITU-T.

3.3.5. GTC layer control plane

The GTC layer control plane is mainly operated via the PLOAM message protocol and some overhead fields referred to as Embedded OAM. It includes the following management functions:

- PMD layer management — configuration of upstream overhead; monitoring health of physical layer, and generation of alarms or statistics accordingly.
- GTC layer management — configuring GTC framing options, such as usage of upstream/downstream FEC, requesting PLOAM, DBRu, and so on.
- Encryption management — GTC mandates Advanced Encryption Standard (AES) as its downstream encryption mechanism, with a per-ONT encryption key. Encryption may be selectively applied on a per GEM Port ID basis. A procedure is defined for key exchange.
- ONT activation — the GTC layer defines the process to activate an ONT on the GPON network, including a ranging procedure to measure the ONT distance and set its equalization delay. The optical power level of the ONT may also be tuned.

The OMCI channel is used to manage the service defining layers that lay above the GTC and it will be described later.

3.3.6. Security

Since the downstream data from the OLT is broadcasted to all ONTs in a specific PON, the information transmitted can be seen by all users. To avoid the eavesdropping an information security mechanism is used to ensure that users are not allowed to access data that is not intended for them.

Because the PON has the unique property that it is highly directional, an ONT cannot observe the upstream traffic from the other ONTs on the PON. This allows privileged information (like security keys) to be passed upstream in the clear. The only way to access this information will be by tapping the common fibers of the PON, which is not considered realistic because it will have to be done in public spaces, and it would probably impair the tapped PON.

GPON uses the advanced encryption standard (AES) mechanism to protect the information payload of the data field in the frame. By using encryption the data is transformed in an unintelligible format at the sending end to protect against unauthorized disclosure, modification, utilization, or destruction.

The AES algorithm is a block cipher that encrypts and decrypts 128 bits data blocks from the original format called plaintext to an unintelligible format called ciphertext. The cipher keys can be of 128, 192, or 256 bits - this makes the encryption difficult to compromise.

The OLT and ONT have a Port ID configured and the key is registered in their active key registers. The key exchange is initiated by the OLT by sending the key request message in the PLOAM channel. The ONT responds by generating, storing, and sending the key.

The AES algorithm requires the generation of a series of round keys based on a single key. This key scheduling operation takes time, and so it must be done in anticipation of the key switch. At the moment the key switch bit is changed, both OLT and ONU must be ready to use the new key.

The user authentication and authorization can also be enforced by using an external database through the use of the remote authentication dial-in user service (RADIUS) protocol.

Authentication can also be employed at the user port using 802.1 x authentications through a RADIUS server that will not allow for data to be exchanged before the port is opened.

Beyond the user port filtering can be done for invalid traffic at Layer 2 using a secured MAC learning scheme for the forwarding database. This can limit the maximum number of MAC addresses per port, prevent the learning of duplicate MAC addresses on different ports in the same VLAN, and eliminate broadcast storms. In addition, the GPON blocks direct Layer 2 user to user communication to protect the network and limit unauthorized usage. User to user communication is allowed only via the Layer 3 routed network.

3.3.7. Forward Error Correction

FEC is based on transmitting the data in an encoded format and is implemented at the transport layer. The encoding introduces redundancy, which allows the decoder to detect and correct the transmission errors. By using FEC data transmission with low error rate can be achieved, and retransmissions are avoided. Because of this, using FEC can result in an increased link budget by up to 6 dB. Therefore, higher bit rate and longer distance from the OLT to the ONTs can be supported, as well as higher number of splits per PON.

In FEC redundant information is transmitted with the original information and if some of the original data is lost or received in error, the redundant information is used to reconstruct the data. In order for the FEC scheme not to use to much additional bandwidth the amount of redundant information is usually small. The Reed-Solomon (RS) FEC codes are best suited for optical signals. The code changes 239 data bits into 255 transmitted bits adding about 7 percent overhead

The FEC solution must support cases where the OLT communicates simultaneously with both FEC supporting ONTs and non-FEC supporting ONTs. In order to achieve the downstream and upstream interoperability between the OLT and ONTs the following rules have to apply:

- The OLT should be able to encode or not encode the downstream data;
- The FEC encoding status (on/off) will be sent to the ONTs using the FEC bit of the Ident field;
- Each ONT should be able to decode or not decode the received data (assuming it is encoded). By using a Block-based RS code, the location of the parity bits is known in advance. As a result, the ONTs that do not support FEC can skip the parity bits, and fully retrieve the original downstream data without FEC decoding;
- Each ONT may or may not FEC encode the upstream data;
- The OLT sets the ONT FEC encoding status (on/off) using the FEC bit in the Flag field;
- The OLT must be able to decode or not decode the incoming upstream data (assuming it is encoded).

No upstream FEC will be used while the ONT is outside of the normal operating state, like activation and ranging. This is required because of the short length of the special transmissions that occur in the non-operating states, and to the rare occurrence of special transmissions.

3.3.8. ONT Activation

GPON uses a full digital in-band activation method to measure the logical reach distances between each ONT and the OLT. After the ONT is ranged, it can be operational - the maximum range of the PON is at least 20 km. When ranging new ONTs, the working ONTs must temporarily stop transmissions, thereby opening a ranging window. Information about the position of the new ONTs can minimize this duration, but for the ONTs that have not been previously ranged, the duration is determined according to the maximum differential range of the PON. After a valid ranging response with a matching ONT ID and serial number is received by the OLT, within the expected time limits based on the maximum length of the PON, the equalization delay can be measured.

The equalization delay is an internal delay in the ONT, set and controlled by the OLT. The purpose of this parameter is to delay the upstream transmission so it arrives at the OLT at the correct phase. The transmission delay measurement for each ONT should be capable of being performed without disrupting service to other ONTs.

Like mentioned before the GPON activation protocol relies on the unique serial number of the ONT for identification and provisioning purposes. There are two types of installation methods of ONTs:

1. The serial number of an ONT is registered at the OLT in advanced by the Operation System (OpS). If the OLT detects an ONT with a serial number that is not registered it will be declared as an unexpected ONT.
2. The serial number of the ONT is not registered at the OLT by the OpS. The automatic detection of the serial number of the ONT is then required. When an ONT is detected, an ONT ID is assigned and the ONT is activated.

The following triggers exist for initiating the ONT activation:

- The activation process is enabled when it is known that a new ONT has been connected;
- The OLT automatically initiates the activation process, if one or more of the previously working ONTs are not detected, to see if those ONTs can return to service. The frequency of polling is programmable under instruction of the OpS;
- The OLT periodically initiates the activation process, testing to see if any new ONTs have been connected. The frequency of polling is programmable under instruction of the OpS.

3.4. G-PON MANAGEMENT

Network operators require full management of GPON equipment and services, while supporting interoperability between ONTs and OLTs of different vendors. ITU-T G.984.4 - Gigabit-capable Passive Optical Networks (GPON): ONT management and control interface specification - describes the ONT management and control interface (OMCI) to address those requirements.

OMCI operates on a dedicated bidirectional virtual channel between the management station and the ONT. The management station can be on OLT itself or another network element.

OMCI comprises a full ONT management information base (MIB), and the ONT management control channel protocol (OMCC) that conveys MIB information between the OLT and ONTs. The MIB comprises a set of managed entities, each containing a set of attributes. Creation of managed entities and their attributes is designated to either the OLT or ONT.

Since GPON ONTs may support a broad variety of interfaces and services, OMCI modeling is very rich in content. However, each MIB instance, representing a specific ONT, contains a small subset of objects. OMCI models physical aspects of the ONTs, such as their equipment configuration, power, and various port types, such as plain old telephone service (POTS), Ethernet, xDSL, T1/E1, radio frequency (RF) video, and MoCA (Multimedia over Coax Alliance). At the service layer, OMCI covers high-speed Internet access using various flow classifications and quality of service (QoS) schemes, TDM-voice, voice over IP (VoIP), circuit emulation service (CES), IPTV, and more. For each of those objects OMCI supports configuration, fault, and performance management. Additionally, OMCI standardizes the software download for OTUs and the housekeeping of the MIB itself.

3.5. GPON Deployment scenarios

The fiber to the home scenario (FTTH) is used to connect residential customers. A single family unit (SFU) is placed usually outside of a house and is typically powered by an UPS to provide continuous service in case of a power failure.

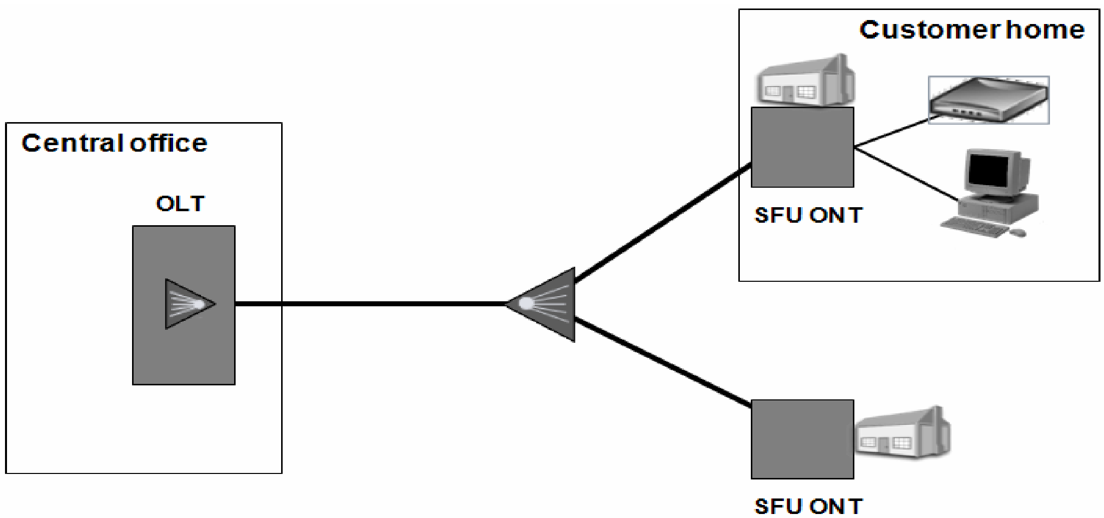


Figure 19. GPON Deployment SFU

Fiber to the building scenario can serve a residential multiple dwelling unit (MDU). For older buildings a typical topology is based on routing a fiber to the MDU and then using the existing copper in the building to distribute services.

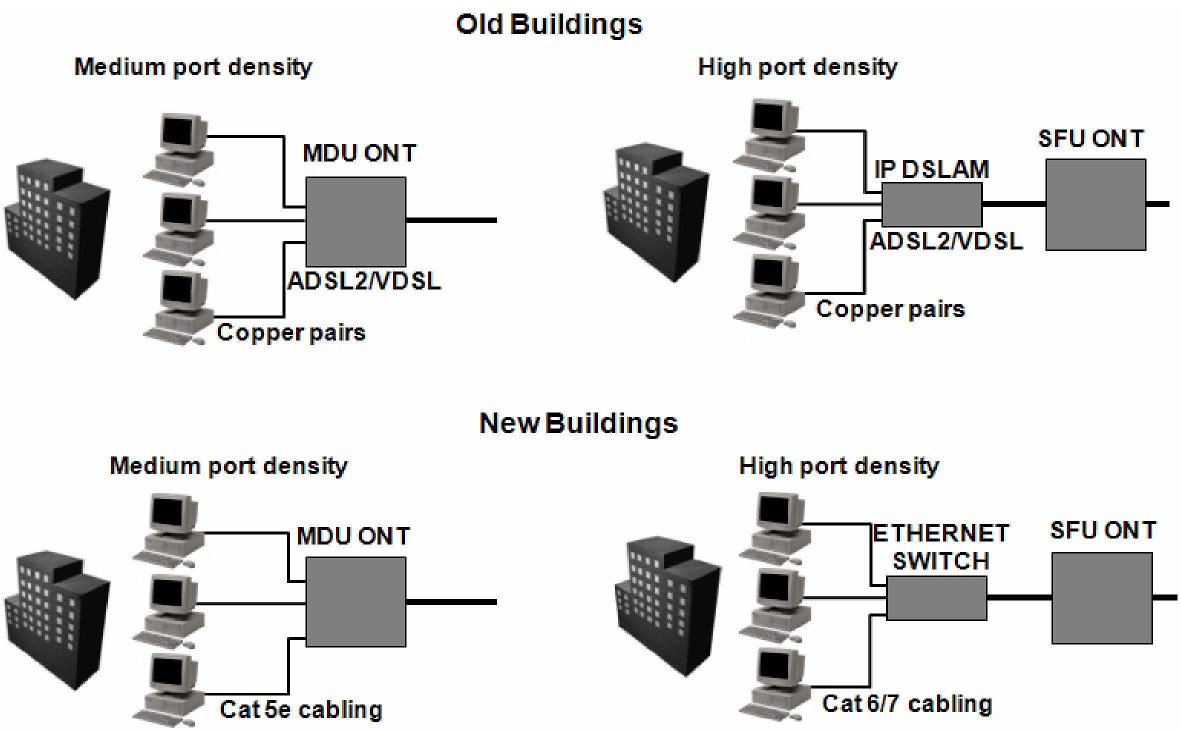


Figure 20. GPON Deployment – MDU

Fiber to the business/curb/office scenario can be used for connecting small, medium, or large corporation.

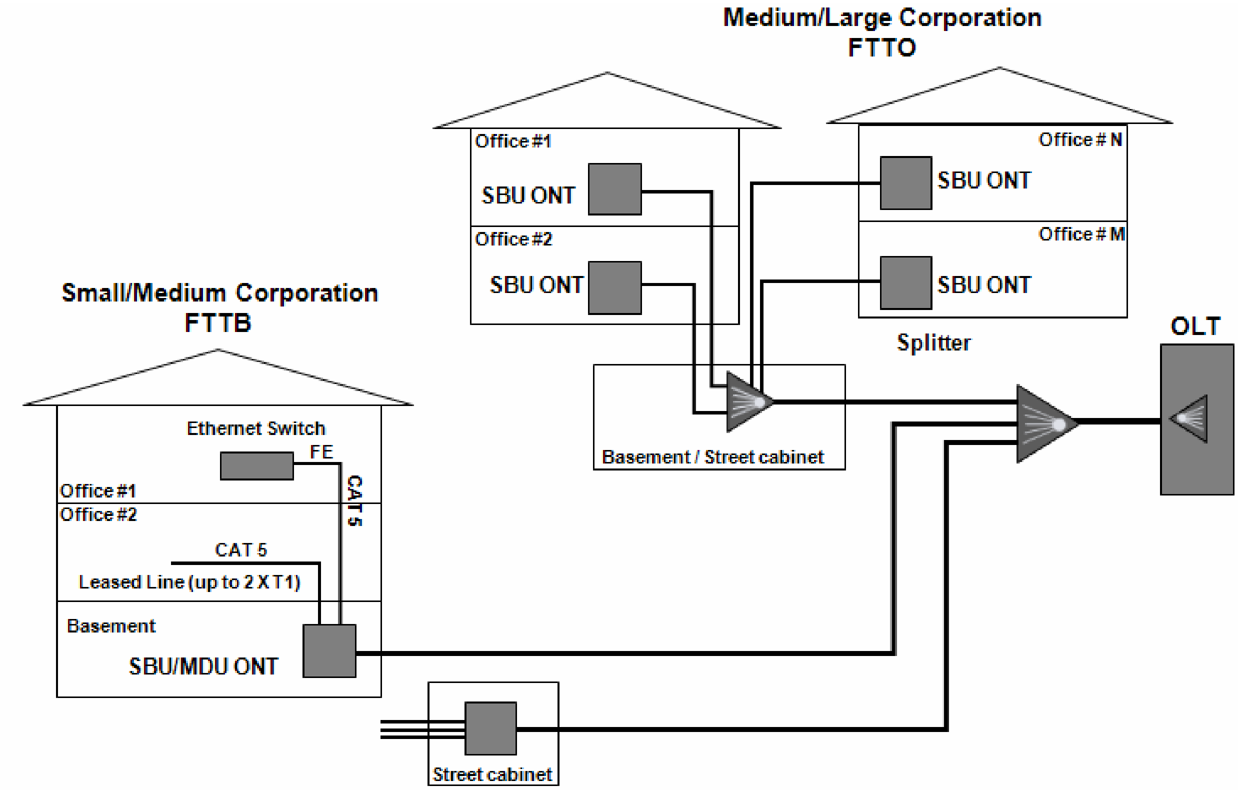


Figure 21. GPON Deployment – Business

3.6. The Future of GPON

One of the GPON enhancements currently in the work is the Next Generation PON (NG-PON). NG-PON spans 100 km between the OLT and up to 512 ONTs, which means far fewer central offices and far less costs for carriers. With 10 Gbps downstream and 2.5 Gbps upstream, it will be able to serve many more subscribers, and at the same time will deliver higher rates.

The WDM PON has also been actively researched as a potential technology. This PON uses multiple wavelengths in a single fiber to multiply the capacity without increasing the data rate. One option considered is the use of “smart CWDM upgrade” by multiplexing 4 wavelengths for downstream traffic and 1 for the upstream traffic. Studies are also made to use DWDM with 1 wavelength per subscriber. To achieve this different realizations have been proposed, of which a majority focus on the network architecture in which a passive wavelength router is used to replace the passive splitter in the PON fiber plant. As a result of this, each OLT-ONT pair will have a dedicated and permanent wavelength assignment, and will require two transmitter / receiver pairs to form a point-to-point link. A passive wavelength router located at the remote node is realized by arrayed waveguide grating (AWG) or a set of thin film filters (TFFs). An AWG can operate over multiple free spectral ranges, permitting use of the same device for both downstream and upstream transmission. If the research in this technology will be successful, and the implementation costs acceptable for carriers, then the definition of wavelength blocking filters will be essential for the deployment. These filters would be supported at GPON ONTs to ensure that next-generation ONTs using additional wavelengths could in the future be installed on currently deployed GPON optical data networks side by side with GPON ONTs.

4. Installation and Commissioning of FlexLight Optimate

4.1. MINT Lab FlexLight Equipment

In this chapter we give a short description of the GPON FlexLight equipment acquired by University of Alberta MINT program.

4.1.1. Optimate 2500LT Overview

Depending of the WAN/Metro interfaces required and of the desired configuration the 2500LT FlexLight OLT shelf can be equipped with a variety of cards as seen in Figure 19:

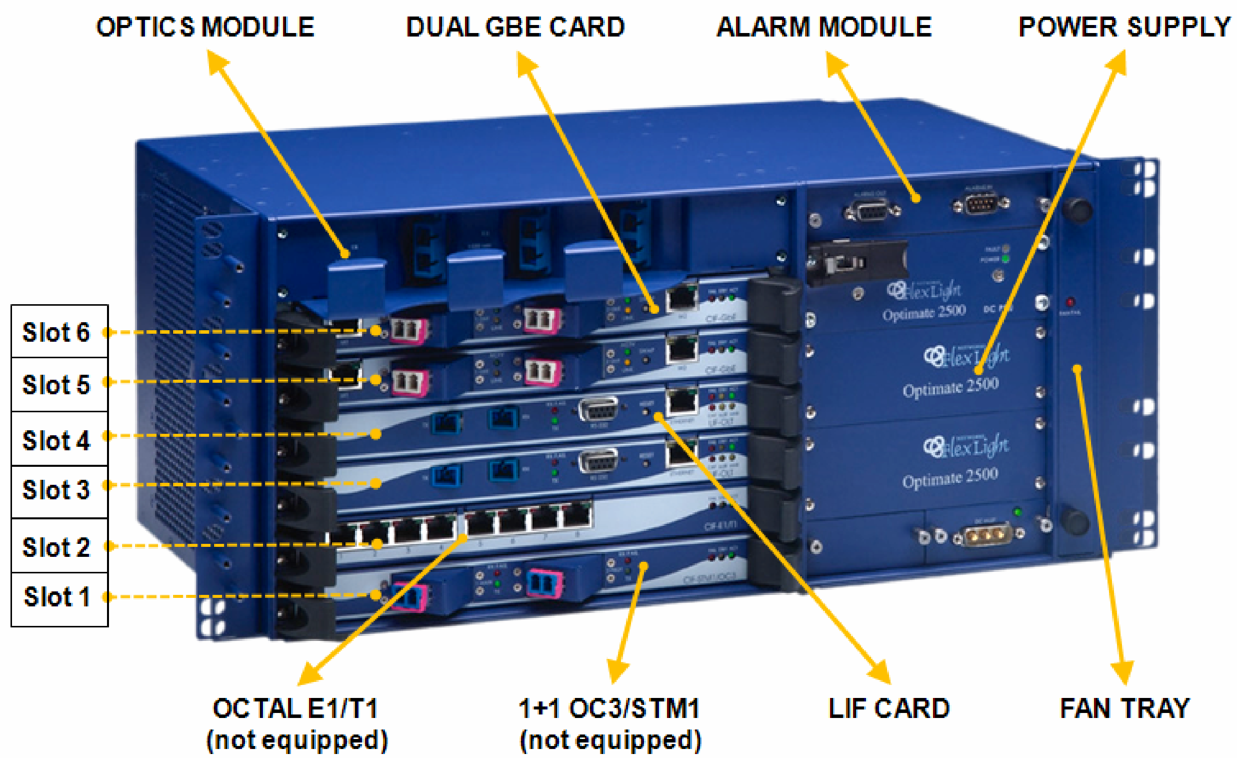


Figure 22. 2500LT Shelf

Note: cards marked as “not equipped” are not available for the MINT shelf.

The FlexLight OLT shelf is grounded through a grounding screw located at the back of the shelf. The grounding wire gauge should be AWG 14-16.

All OLT cards are hot swappable and therefore can be installed or removed without powering down the OLT.

All interface cards (slot 1 to 6) have generic LEDs describing the card mode of operation. In addition to the generic LEDs, specific cards have dedicated LEDs according to card's functionality.

When inserting a card into the OLT shelf, the following LED behavior is noted:

1. All LEDs light up: automatic LED test;
2. During the upload process, the standby LED blinks;
3. For each assigned/configured port, the associated LED is lit.

When equipping the OLT with cards the following rules apply:

1. GPON Line Interface (LIF) card must be inserted into slot 4. A second LIF card can be installed in slot 3 if one of the following configurations is desired:
    - LIF redundancy – protected PON,
    - Dual PON configuration;
2. Metro Interface cards (CIF) can be inserted in slots 1, 2, 5, 6. Slot 3 can also be used if the OLT shelf is not equipped with a second LIF card.

For cooling purposes, if not all the slots are equipped, the shelf is fitted with dummy panels. When removing or replacing cards from the shelf remove existing cables (if applicable), move the front panel latches to the open position, loosed the screws and remove the card carefully by pulling it out of the slot.

The 2500LT backplane, 10Gbps total throughput, allows interconnecting all the cards to the LIF cards. In order to cater for an option of redundancy or dual PON capacity, each CIF card can use two parallel buses, each connected to a dedicated LIF card.

The MINT OLT shelf is fitted with the following cards:

- Alarm module ,
- Power supply modules – 3 are used and are designed to operate in a load sharing 2+1 mode: 2 to provide power for a fully equipped shelf, 1 is used for redundancy purposes,
- Optical drawer – the spare is modified to support 2 PONs,
- LIF card in slot 4 (a second one is available as spare or can be used for a different configuration),
- GBE card in slots 1 and 6 – currently only the one in slot 6 is used.

4.1.1.1. LIF Card

The LIF card interfaces with the PON and provides 2.488 Gbps bit rate downstream on 1490 nm wavelength and 1.244 Gbps bit rate upstream on 1310 nm.

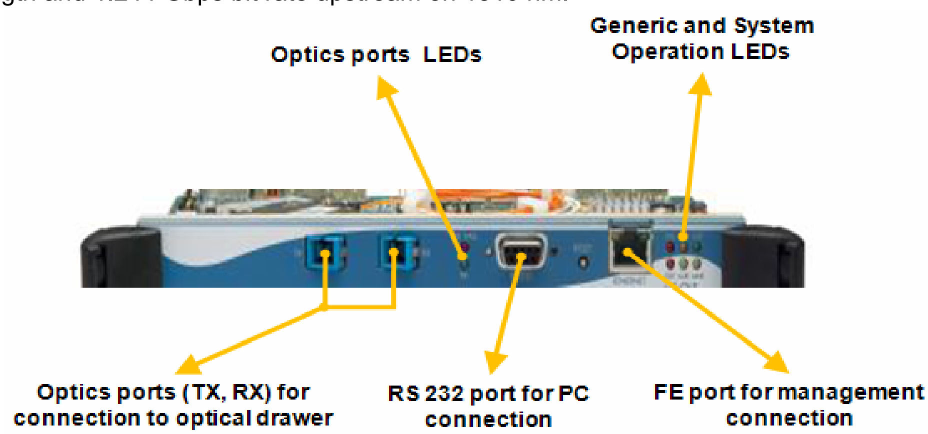


Figure 23. LIF Card

	LED	STATUS	DESCRIPTION
Generic LED	ACT	Green	Indicates that the card is connected and receiving electrical power
	STBY	Yellow	Indicates that the card is in standby state
	FAIL	Red	Indicates that the card is not receving power, or a physical equipment error
System Operation LEDs	Critical	Red	Indicates a critical alarm
	Major	Orange	Indicates a major alarm
	Minor	Yellow	Indicates a minor alarm
Optics ports LEDs	TX	Green	Indicates that the card is transmitting
	RX FAILURE	Red	Indicates that no signal is received

Table 8. LIF Card LEDs Description

4.1.1.2. GBE Card

GBE card aggregates the PON traffic and interfaces with the Metro network.

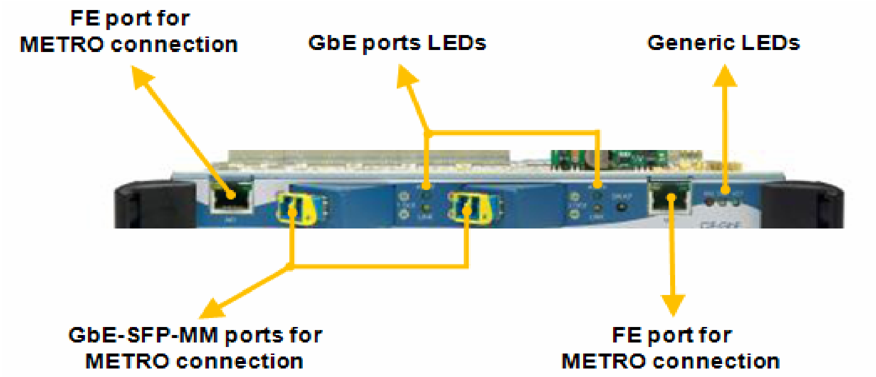


Figure 24. GBE Card

	LED	STATUS	DESCRIPTION
Generic LED	ACT	Green	Indicates that the card is connected and receiving electrical power
	STBY	Yellow	Indicates that the card is in standby state or during download operation
	FAIL	Red	Indicates that the card is not receving power, or a physical equipment error
GbE Ports LEDs	ACTV	Green	ON - the port is operational (a signal is being detected)
			OFF - no signal is being detected
	LINK	Red	ON - link up
			OFF - link down

Table 9. GBE Card LEDs Description

4.1.1.3. Optical Drawer

The optical filters and CWDM multiplexers are located in the optical drawer that resides in the top tray of the OLT. This tray is situated above Slot 6, and consists of a flat tray with passive optical devices fixed on it. As a result there is no backplane power feed to this module.

There are 2 optical drawers in the MINT lab. As mentioned before the optical conections in one of them (labeled as Dual PON) were modified in order to permit a dual PON OLT configuration.

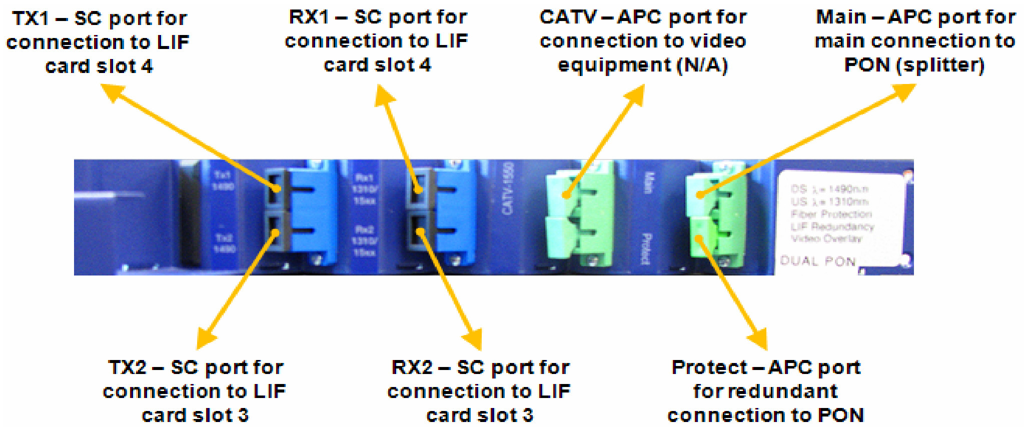


Figure 25. Optical Drawer

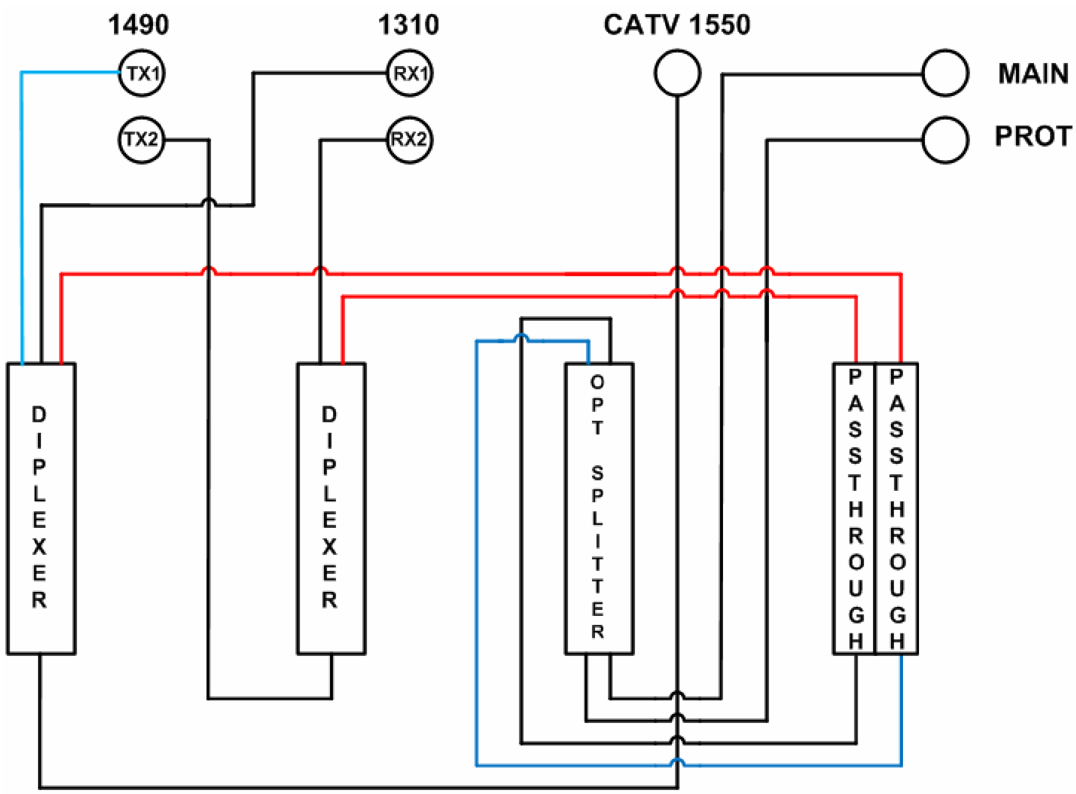


Figure 26. Optical Drawer Layout – Single PON

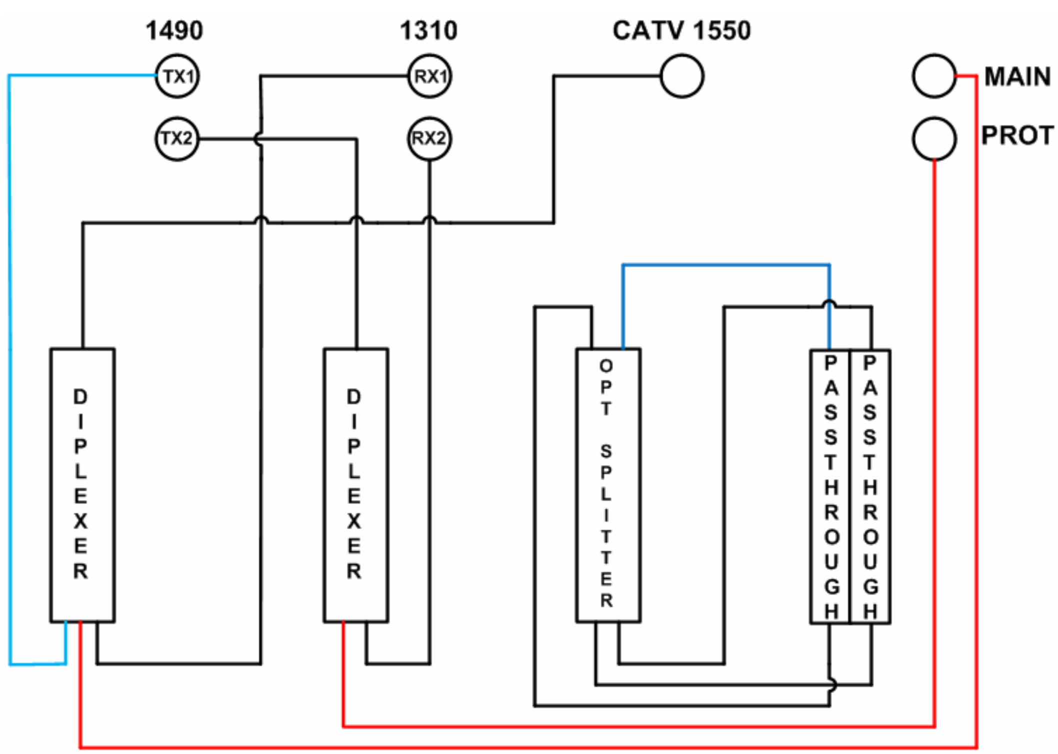


Figure 27. Optical Drawer Layout – Dual PON

4.1.2. Optimate ONT Equipment Overview

The 1000NT is a 1U device that has three user selectable service slots that can be equipped as follows:

- 4 E1/T1 and 4 10/100 BaseT Ethernet card,
- 8 10/100 BaseT Ethernet card (MINT lab unit not equipped),
- RF Analog Video Interface (MINT lab unit not equipped),
- 8-Port POTS Card (MINT lab unit not equipped).

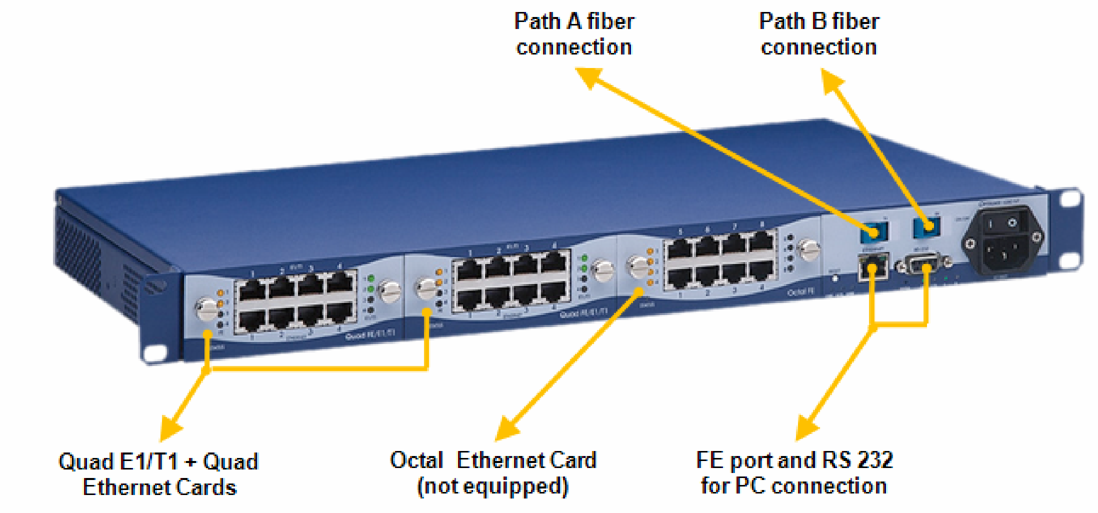


Figure 28. 1000NT MDU ONT

The 510NT ONT is located inside the customer's business building or residential house.

Figure 29. 510NT ONT Front View

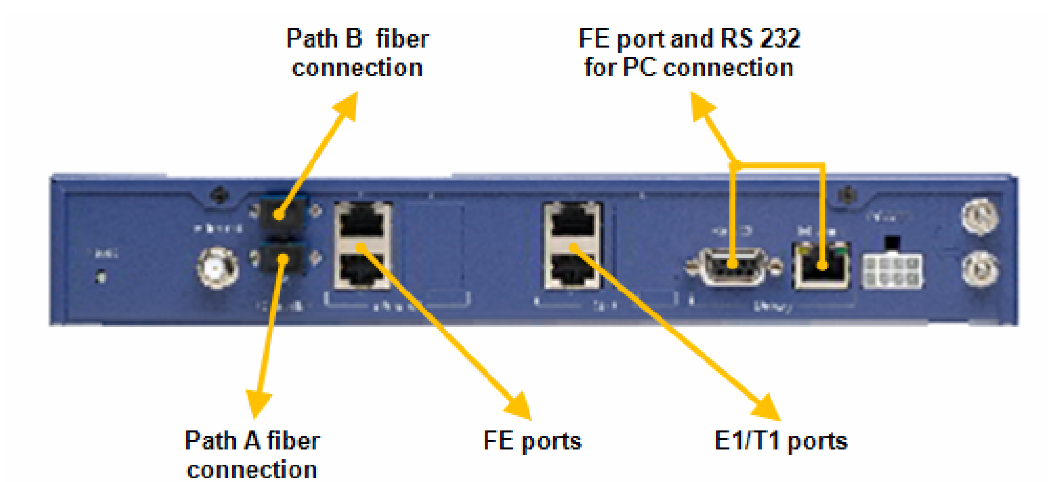


Figure 30. 510NT ONT Rear View

	LED	STATUS	DESCRIPTION
Status	Status	Green	Successful boot
		Blinking Orange	During software boot - transition to green and the end of process
		Red	Prior to software boot start or physical equipment error
System Operation LEDs	Critical	Red	Indicates a critical alarm
	Major	Orange	Indicates a major alarm
	Minor	Yellow	Indicates a minor alarm
Optics	TX	Green	Indicates that the card is transmitting
	LOS	Red	Indicates that no signal is received
	A	Green	Indicates that A path fiber is active
		Red	Indicates that A path fiber has failed
		Off	A path fiber is not used
	B	Green	Indicates that B path fiber is active
		Red	Indicates that B path fiber has failed
		Off	B path fiber is not used
Service	Ethernet	Green	Blinking - port is operational and active
			Steady - port is disabled
		Orange	Link up and no port activity
	E1/T1	Green	Port is working properly
		Red	LOS or AIS

Table 10. 510NT and 1000NT LEDs Description

4.2. MINT Lab GPON Architecture – Single PON

All PON fiber connections should be made when the OLT and ONT's are powered down.

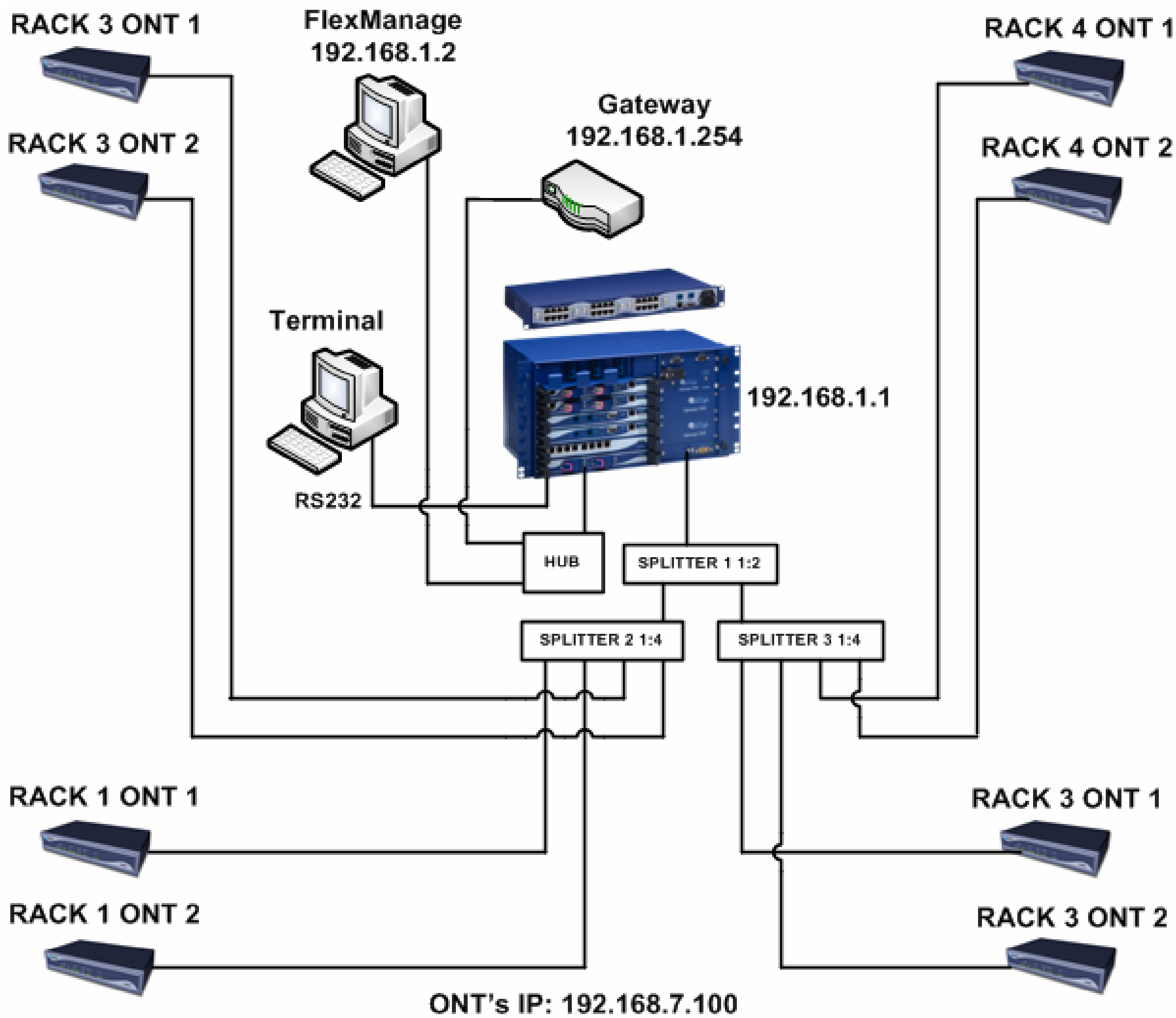


Figure 31. GPON Architecture

Remark: The 1000NT is not used in this configuration – there are no more splitter ports available.

4.2.1. FlexManage Installation

FlexManage, FlexLight's network management solution, is a Web based management system. FlexManage offers monitoring, control and maintenance capabilities over the PON. The set of features implemented support fault analysis, service configuration, and performance monitoring.

The FlexManage and the additional software to support it have to be installed on a Window XP machine which has the firewall turned off. The following steps need to be followed:

1. Install 'Sybase 7.0.3 Database Server':
   - Copy serial number from sn.txt file,
   - Select all defaults,
   - Request "license seats": 100,
   - Skip installing 'Power Dynamo', 'Power Designer', and 'Info Maker';

2. Install 'Microsoft.NET FRAMEWORK 2.0' if not already done – check C:/Program Files;
3. Install 'Microsoft VM':
   - Enable components in the Advanced tab of Internet Explorer Internet Options menu;

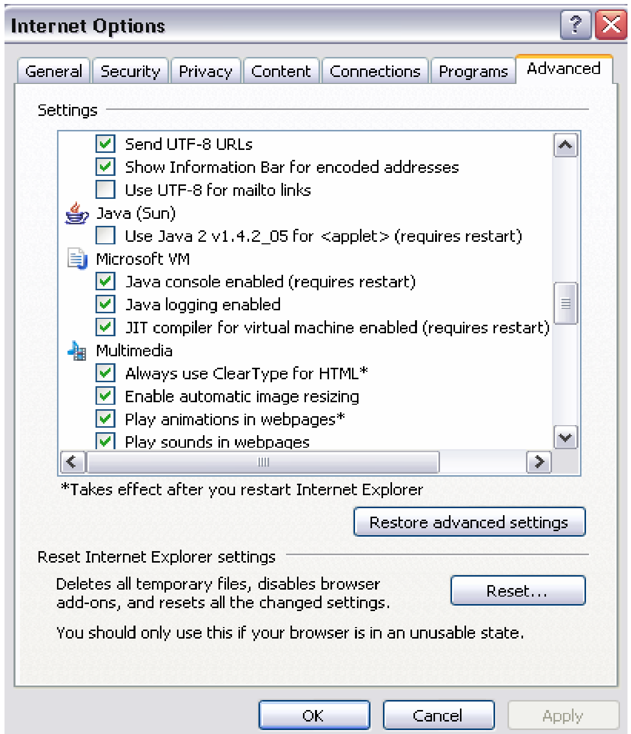


Figure 32. Enabling 'Microsoft VM' Components

4. Copy 'FlexManageSetup.exe' to C drive and run the application,

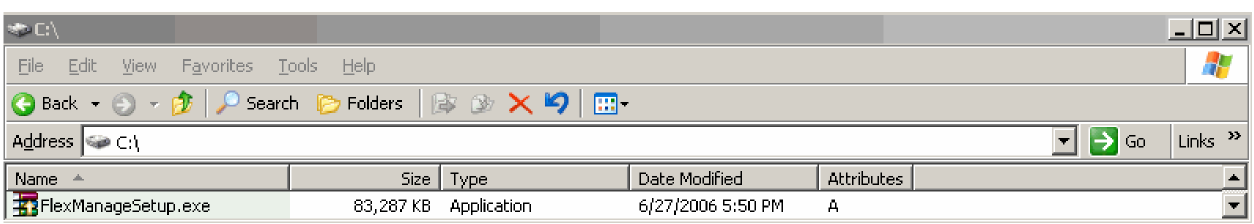


Figure 33. FlexManage Installation

5. Create shortcut for C:\FlexManageVer2\flexms\bat\FlexManageVer2.bat and run it – do not close these application windows as long as FlexManage is used,

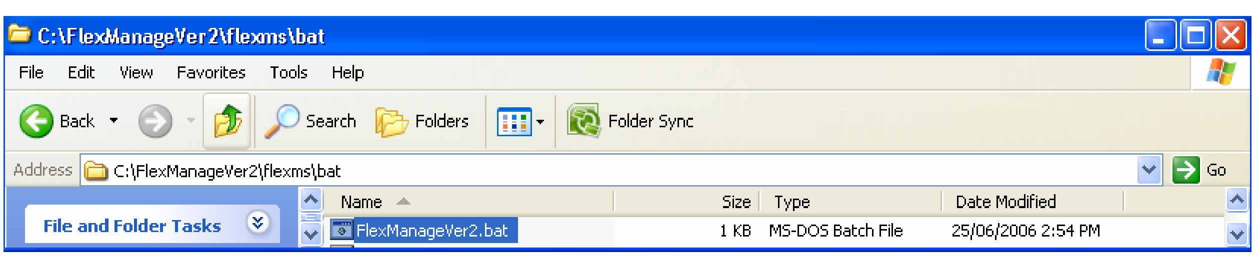


Figure 34. FlexManage Application

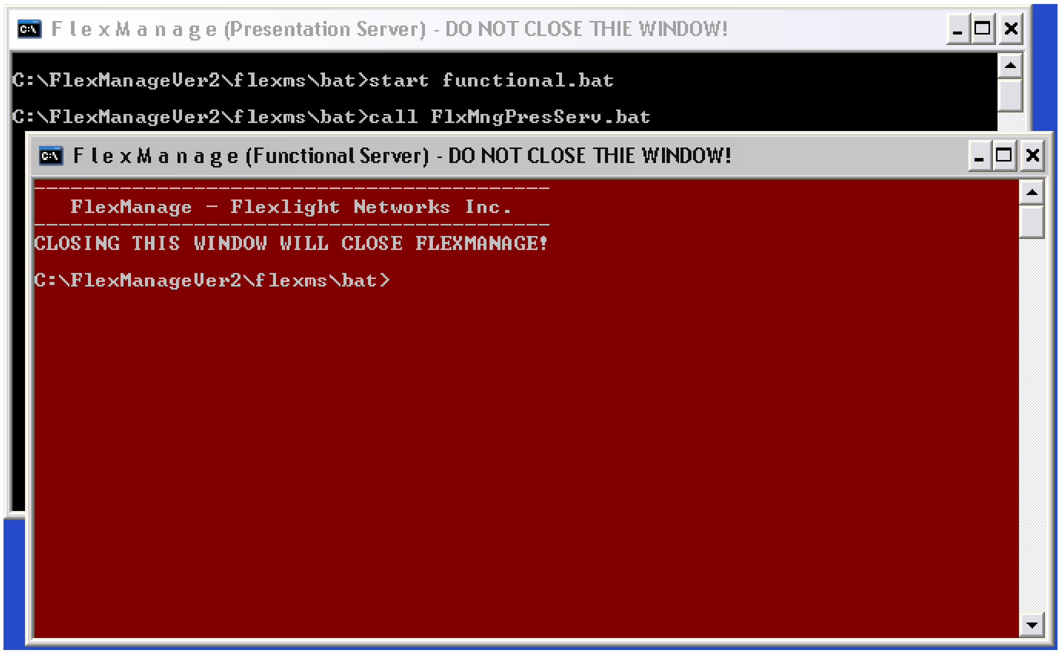


Figure 35. FlexManage Server Application Startup

6. Open Internet Explorer, type http://localhost:8080 in the address bar, and then choose ‘FlexManage.html’ to run the client application. Create shortcut.

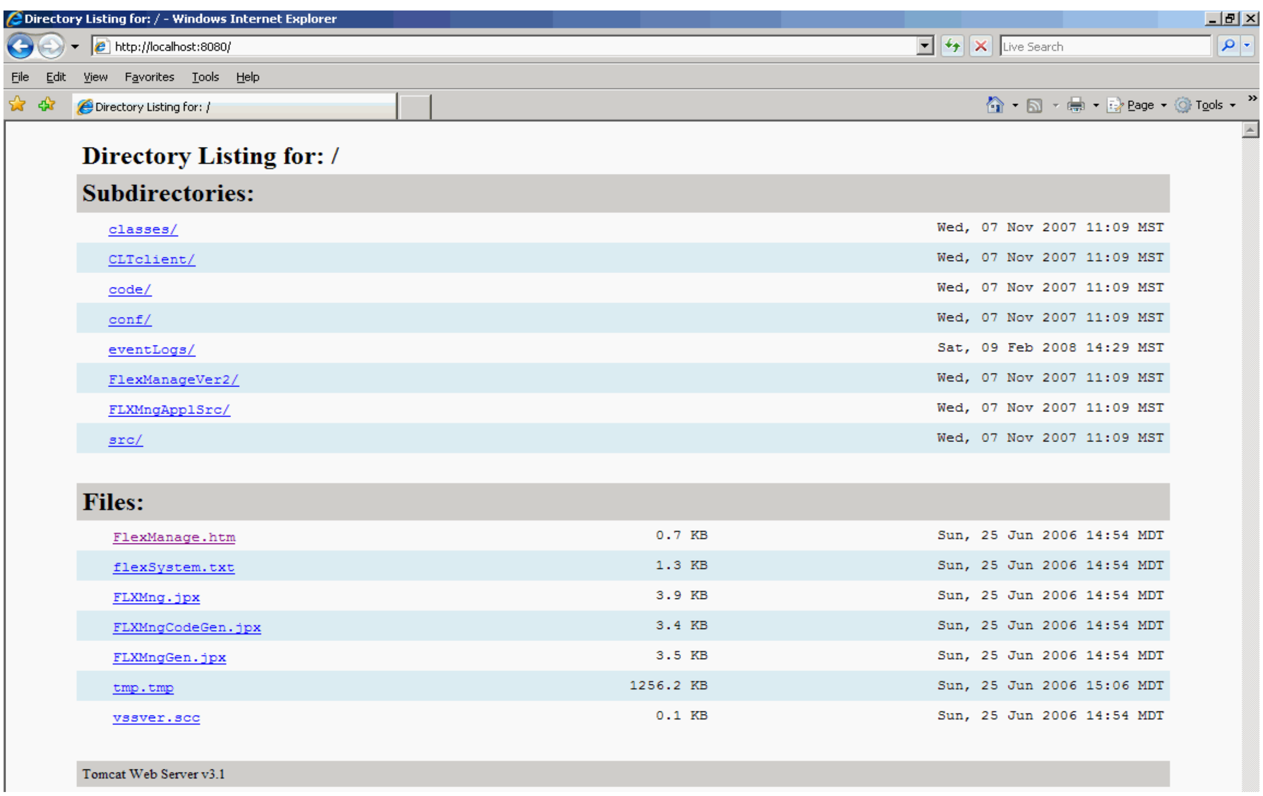


Figure 36. Local Host Directory Listing

In the FlexManage login window use “admin” for User Name and Password.

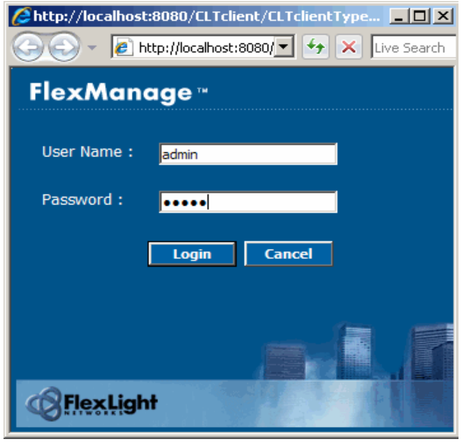


Figure 37. FlexManage Client Login

Set up the Ethernet card IP address and connect the FlexLight server to the ONT LIF card management port.

Remarks:

– There are two FlexManage versions available. Because of the fact that version 2 solved some existing ‘bugs’ in the previous version, and also because is more user friendly, is the one that was installed in the MINT Lab. This version was not officially launched and as a result there is no user guide;
– If the FlexManage server application windows are closed the machine will have to be rebooted.

4.2.2. OLT Configuration

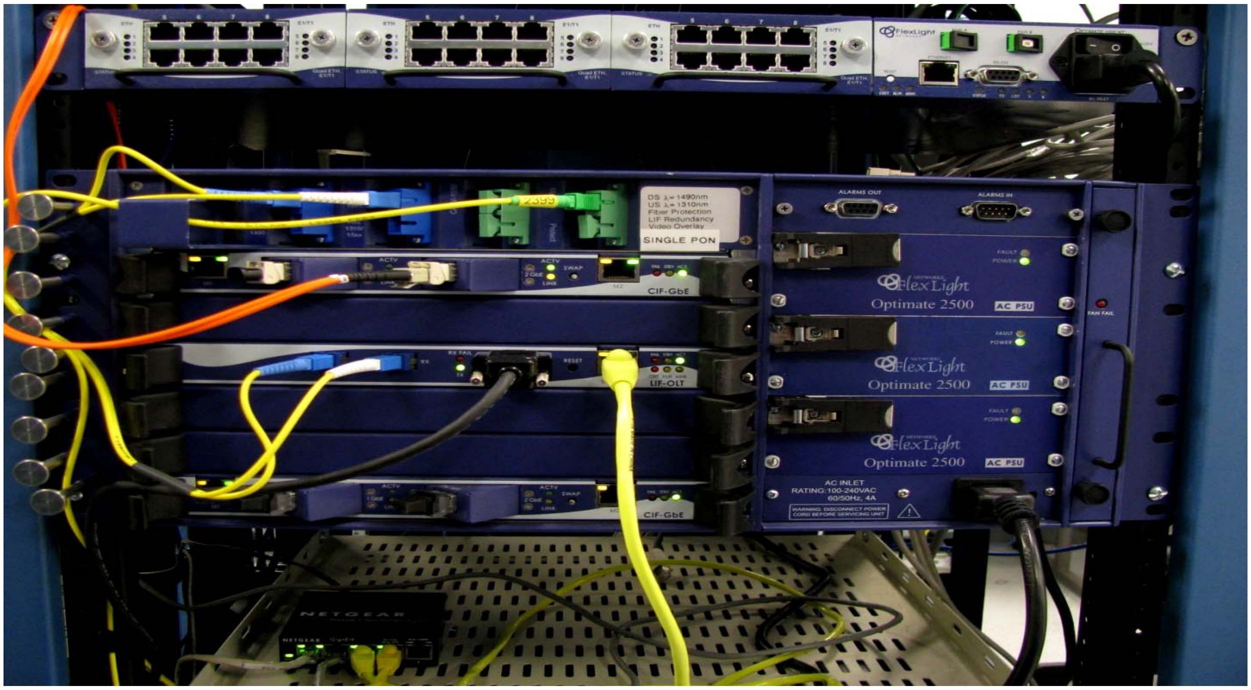


Figure 38. OLT MINT Lab Shelf

Connect PC to the OLT LIF card RS 232 port and use the 'Terminal' application to set up the IP address, subnet mask, and gateway address of the OLT. The connection port in the 'Hyper Terminal' program can also be configured for connection to the OLT:

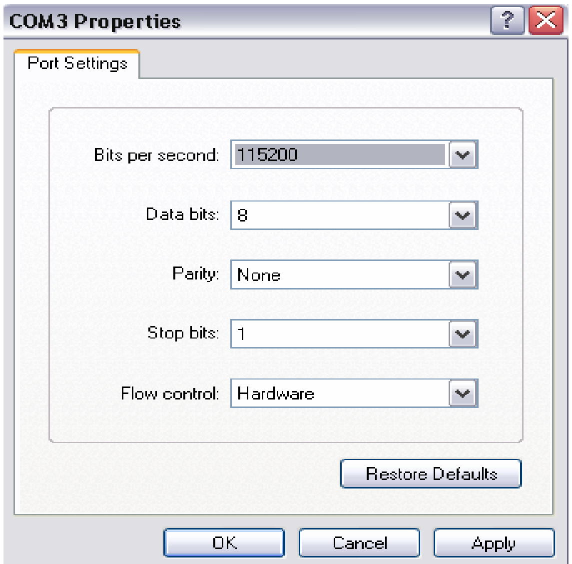


Figure 39. 'Hyper Terminal' Communication Port Configuration

'Terminal' is a command line interface application. Choose the communication port, press "Connect" and then use the enter key. To find out the description and the action resulting from using the right side buttons use the mouse pointer, i.e. for "Login":

- Description: Login,
- Command: setup;echoof;psw SismA-Light.

  The following are general commands that can be used at any time:
- Help – shows the available commands and gives a short explanation,
- List – shows the available directories,
- Up – exits the current level.

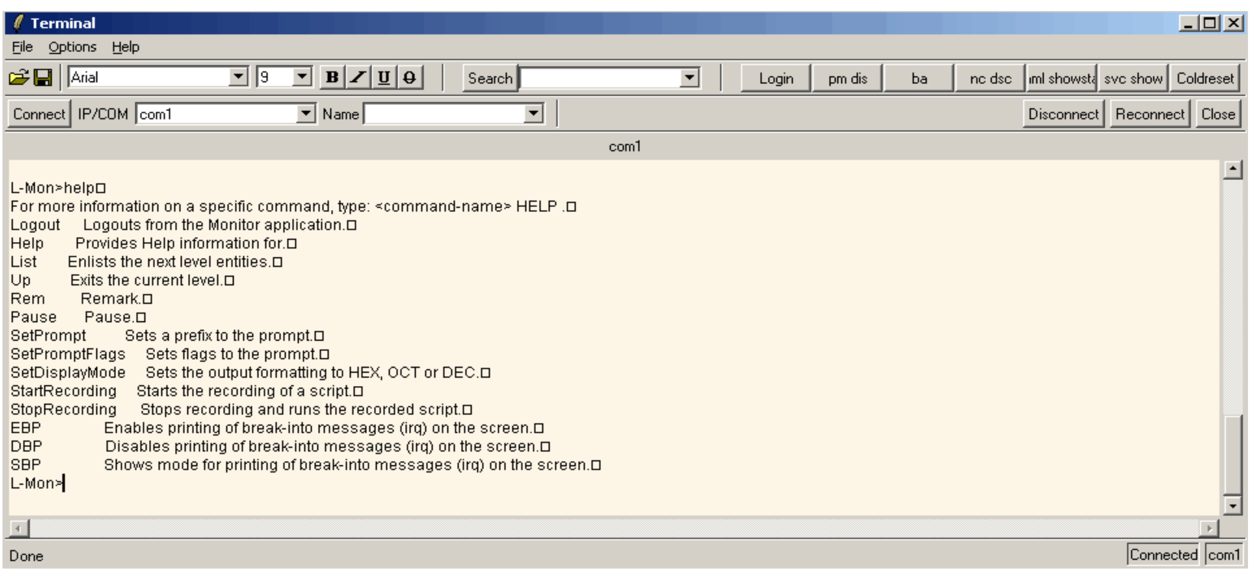


Figure 40. 'Terminal' Application Window

Use the following steps in the “Setup” command mode to configure the OLT:

1. Getip - see current IP address;
2. Setip - change the IP address;
3. Getsubnet - see current subnet mask;
4. Setsubnet - change subnet mask;
5. Getgateway - see current default gateway address;
6. Setgateway - change default gateway address;
7. Reboot cold – reset OLT to activate the new settings.

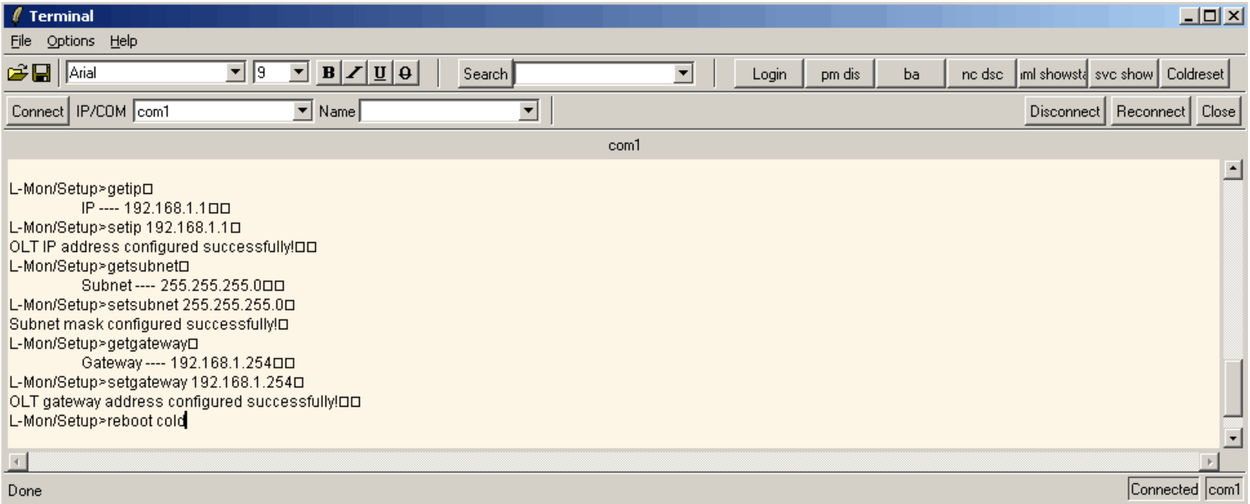


Figure 41. OLT IP Addresses Configuration

If the OLT and the FlexManage server are both connected to the same subnet their subnet mask should be the same and then default gateway parameter can be left empty.

4.2.3. ONT Configuration

Figure 42. 510 ONT’s MINT Lab Front View

Figure 43. 510 ONT's MINT Lab Rear View

Since the ONT is managed and controlled by the OLT there is no need to make any adjustment or changes via a craft terminal.

The 'Ethereal' application has been used to find the IP address for some ONT's and 'Terminal' software was employed, in the same manner as for the OLT, to change it to 192.168.7.100. For the physical connection a CAT5 crossover cable is needed to connect a PC to the ONT craft terminal port. Please note the PC address must be set (i.e. 192.168.7.99) and the firewall must be disabled.

4.2.4. Link Budget and Power Measurements

The received power at the ONT's should be between -3 dB (receiver overload value) and -18 dB.

The received power at the OLT should be between -13 dB (receiver overload value) and -28 dB.

Link power calculations and power measurements need to be made to make sure that the ONT and OLT transceivers receive the right power level. If necessary, appropriate attenuators can be used.

Component	Output / Loss
OLT power (2 - 7 dBm)	+ 7 dBm
Optical drawer	- 4.5 dB
1:2 splitter	- 3.5 dB
1:4 splitter	- 7.0 dB
Connectors (8)	- 2.4 dB
Received at ONT	**- 10.4 dB**

Component	Output / Loss
ONT power (-2 - 3 dBm)	+ 3 dBm
Optical drawer	- 4.5 dB
1:2 splitter	- 3.5 dB
1:4 splitter	- 7.0 dB
Connectors (8)	- 2.4 dB
Received at OLT	**- 14.4 dB**

Table 11. Link Budget

Based on OLT and ONT sensitivity the power level at the receiver end will not reach the overload values even if the maximum transmitter power is used. As a result, no attenuation is needed for this configuration.

The following passive optics parts account for the loss of 4.5 dB at the optical drawer:

- Diplexer – 1 dB,
- 2:2 splitter (for fiber protection and LIF redundancy) – 3.5 dB.

A Power Meter was used to measure the actual received power at different components.

Remark: since the ONT is transmitting in burst mode no measurements can be made for the 1310 nm wavelength.

Component	Measured Output
OLT power (2 - 7 dBm)	+ 4.9 dBm
Optical drawer	+ 0.8 dBm
1:2 splitter - 1 output port	- 3.6 dBm
1:2 splitter - 2 output port	- 3.1 dBm

ONT	Received Level	Through
RACK 1 ONT 1	- 13.3 dBm	Splitter 2 port 1
RACK 1 ONT 2	- 13.1 dBm	Splitter 2 port 2
RACK 2 ONT 1	- 16.1 dBm	Splitter 2 port 3
RACK 2 ONT 2	- 13.2 dBm	Splitter 2 port 4
RACK 3 ONT 1	- 15.9 dBm	Splitter 3 port 1
RACK 3 ONT 2	- 15.3 dBm	Splitter 3 port 2
RACK 4 ONT 1	- 16.2 dBm	Splitter 3 port 3
RACK 4 ONT 2	- 15.9 dBm	Splitter 3 port 4

Table 12. Power Measurements

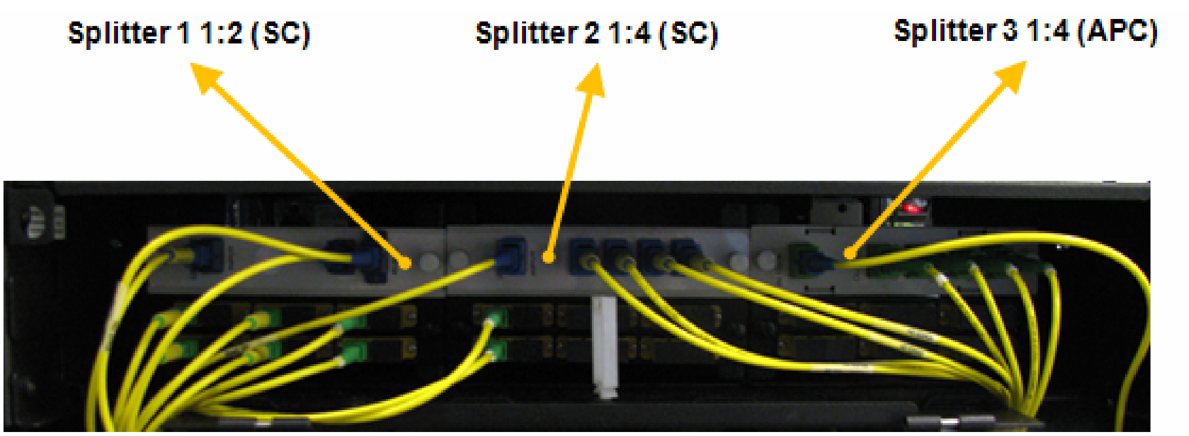


Figure 44. Fiber Enclosure and Splitters

Remarks:

- The third port of splitter 2 is damaged, hence the difference in RACK 2 ONT 1 receiving power compared with the other ONT's connected through the same splitter,
- The received power of the ONT's fed through splitter 3 are lower because there were no more SC to APC fiber patch cords available – more attenuation due to the fact that there is a direct connection between an SC and an APC connector.

4.3. Commissioning of FlexLight GPON solution

The FlexManage is the application used for operation and configuration of the GPON FlexLight equipment. Like mentioned before, the existing PON in the MINT Lab is designed and configured for a single PON with no LIF redundancy or fiber protection. If this configuration needs to be changed examples and explanations to do so are given when necessary.

The Main Window provides a view of the network topology and gives access to all FlexManage functions.

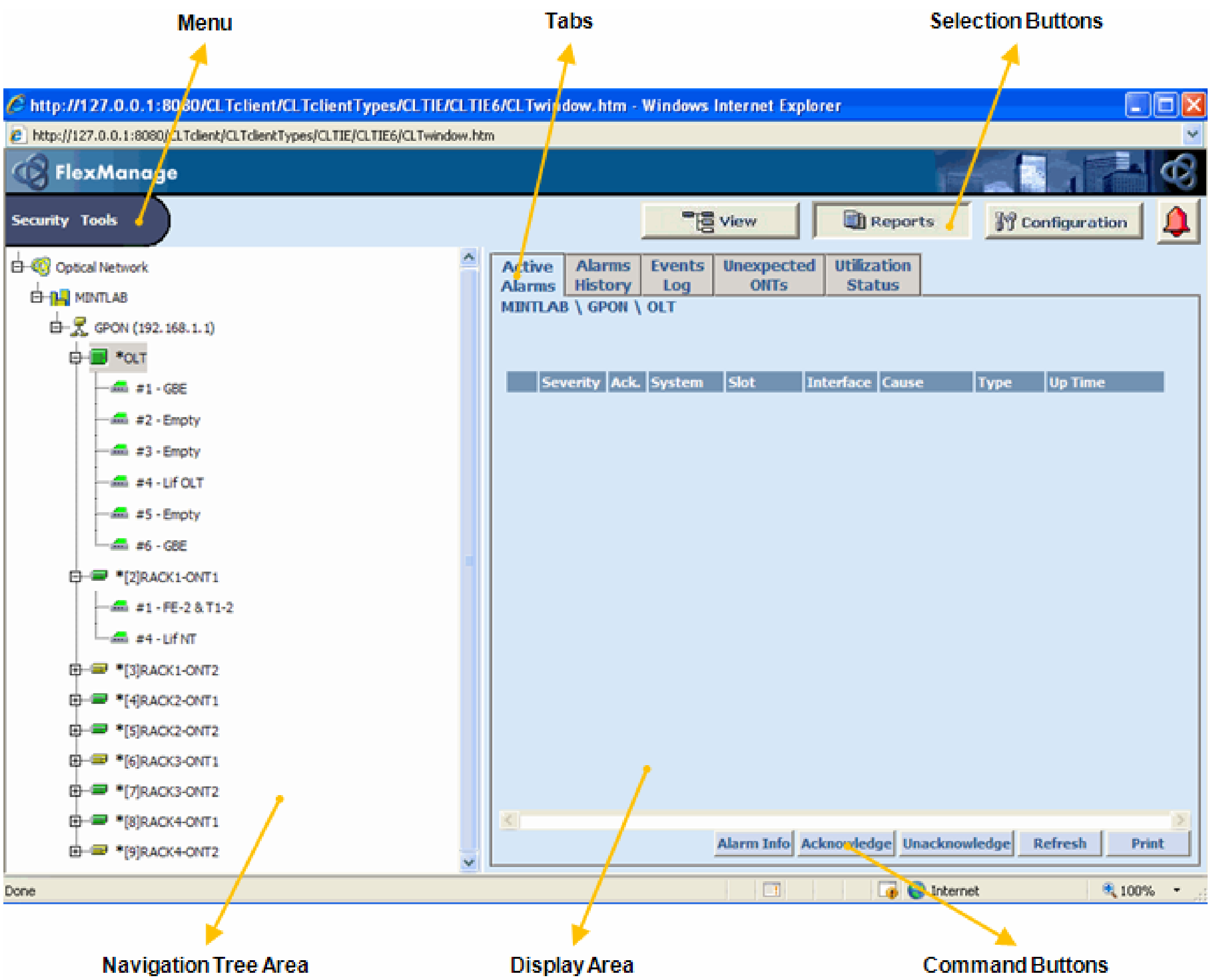


Figure 45. FlexManage Main Window

The Navigation Tree Area of the main window displays the elements monitored by FlexManage in a hierarchical format. Objects displayed in the Navigation Tree include both physical objects, such as cards, and logical objects, such as a subnet or site. Each type of object is represented by a graphical icon:

- - Optical Network: represents the entire managed network;
- - Site: divides the network in several groups;
- - Subnet: site sublayer that contains a single OLT and all ONTs that are connected to that OLT. The IP address of the subnet is displayed next to the subnet name;
- , - Shelves: represents the network element and varies according with the network type;

- - PON Subnet: contains a group of ONTs that are connected to the OLT LIF via a single PON. It is displayed only when the OLT LIF card at slot 3 is configured in dual PON mode. If the OLT LIF card in slot 3 is configured with LIF redundancy, or slot 3 is empty, or the card in slot #3 is not a LIF card, this layer is not visible;
- - Card: represents the cards assigned (expected) to an OLT/ONT. The specific card type is displayed next to the icon;
- - Communication Loss: indicates that a communication loss to the OLT/ONT has occurred;
- - Upload: indicates that an upload process is in progress;
- - Deactivated – indicates that the ONT is not activated.

The Menu includes the Security options that provide access to FlexManage functions. These options are used to create users, groups, profiles, and to change passwords.

The Display Area of the main window displays different window, depending on the selections made.

The following Selection Buttons are displayed at the top right of the display area:

- View;
- Reports;
- Configuration;

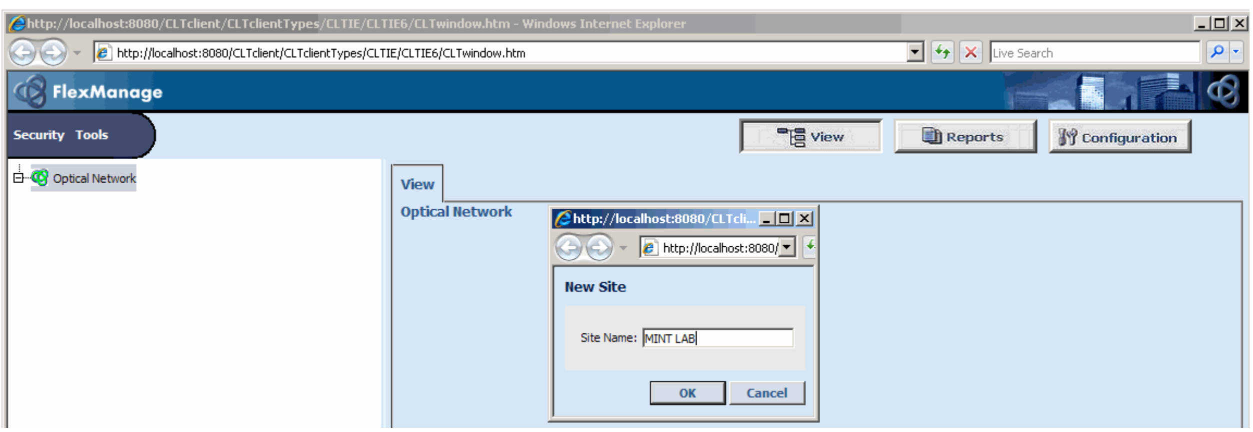
The Tabs displayed and the display area of the main window will vary according to the selection made.

The Command Buttons are displayed at the bottom right corner of the display area and vary according to the selected tab.

The following steps have to be followed to set up the FlexLight GPON:

4.3.1. Add Site

A site can include one or more network elements. To add / delete a site right-click on the Optical Network icon.



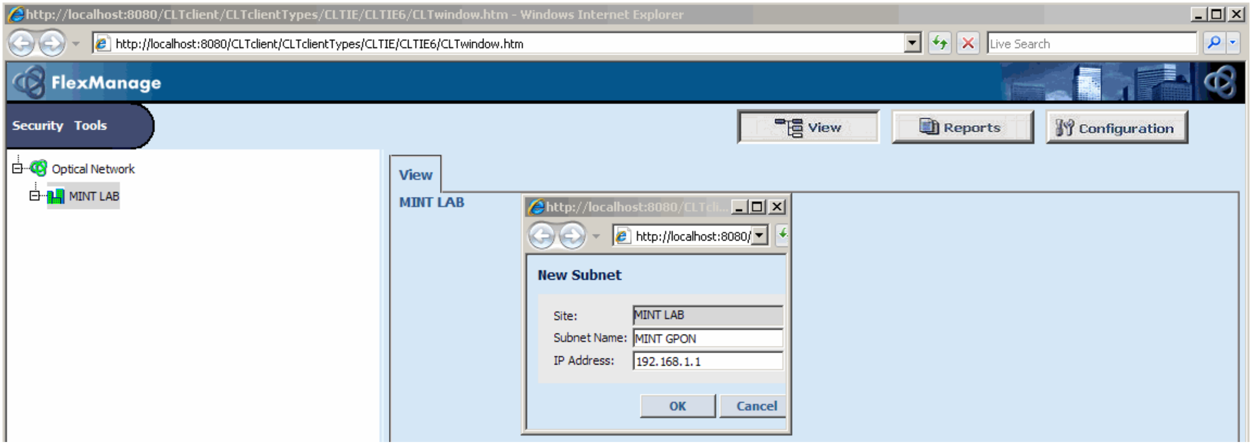
The Navigation Tree Area will be updated with the new site.

4.3.2. Add Subnet

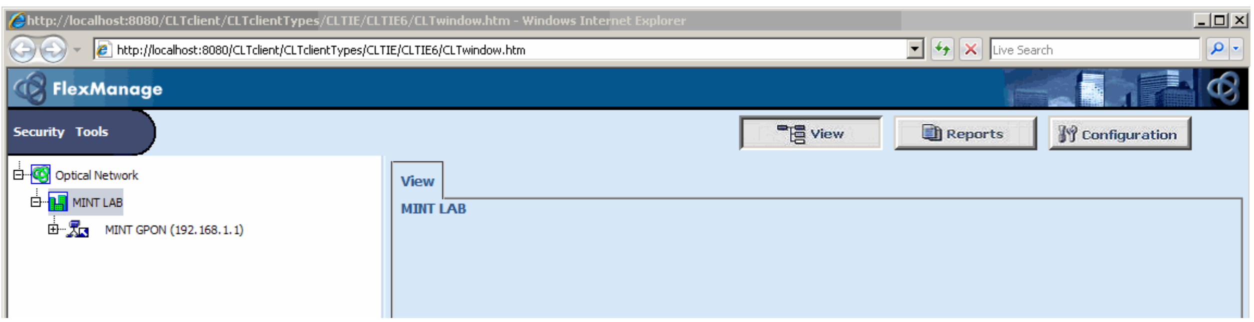
Each subnet will support a single ONT. To add / delete a subnet right-click on the Site icon.

In the dialog box configure the following parameters:

- Site – read only field that displays the site name;
- Subnet Name – type in the desired name; this field will appear in the Navigation Tree Area;
- IP Address – enter the OLT IP address.

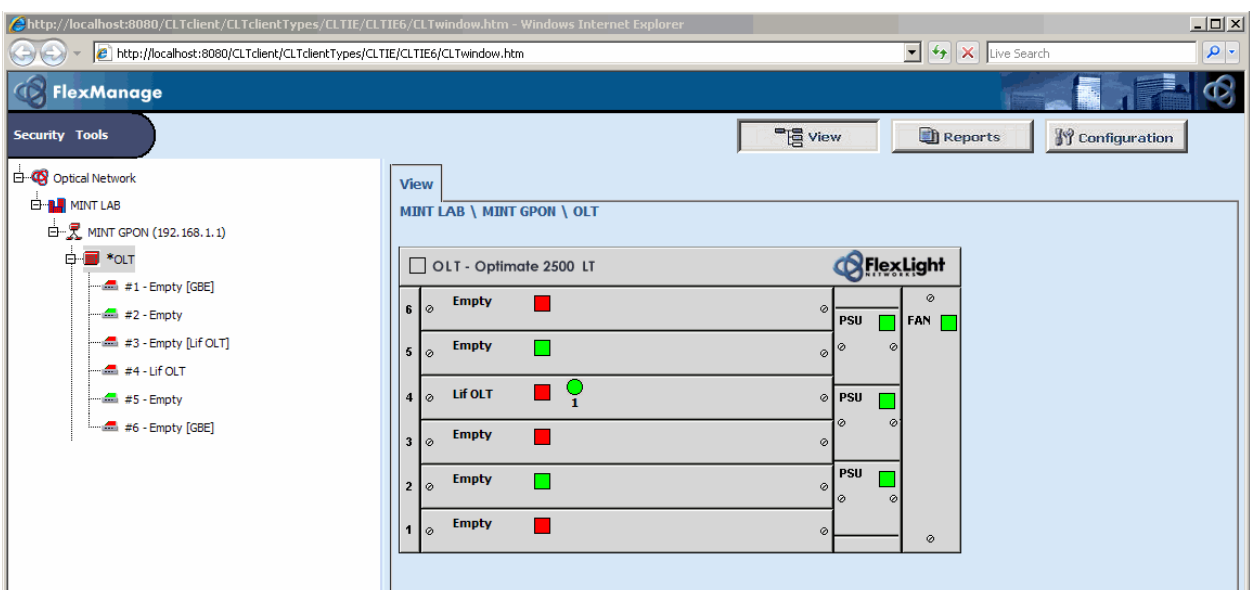


Once the OLT icon is displayed in the Navigation Tree Area the FlexManage will initiate the upload from the OLT's MIB files to update the FlexManage database. After the upload process is complete the OLT icon will be color coded according with the last known most critical alarm.

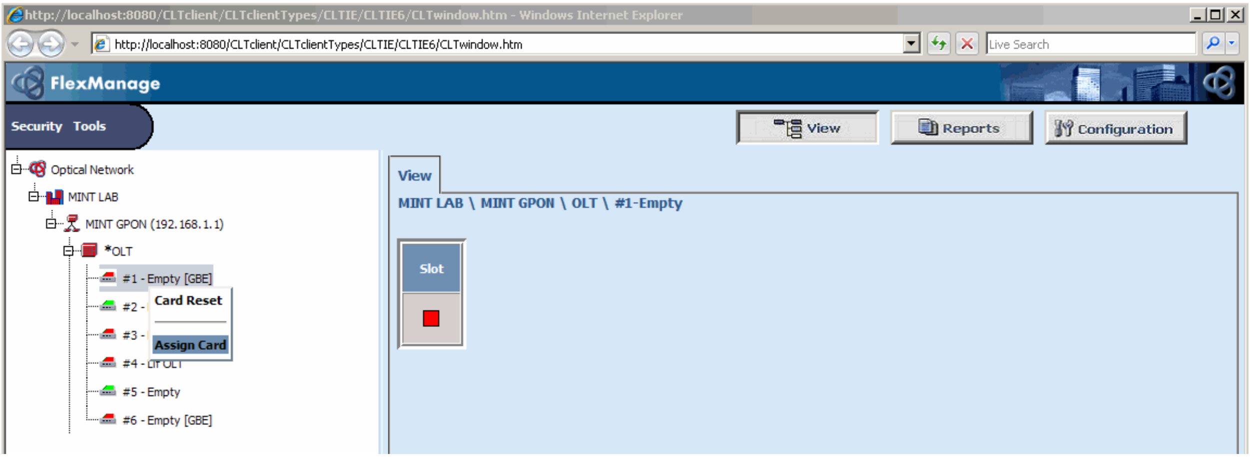


4.3.3. Card Assignment

If the View button is selected the OLT shelf is displayed:



The following procedure is used to populate the OLT/ONT shelves by defining the card that is installed in any given slot. Right click on the slot and choose assign card:

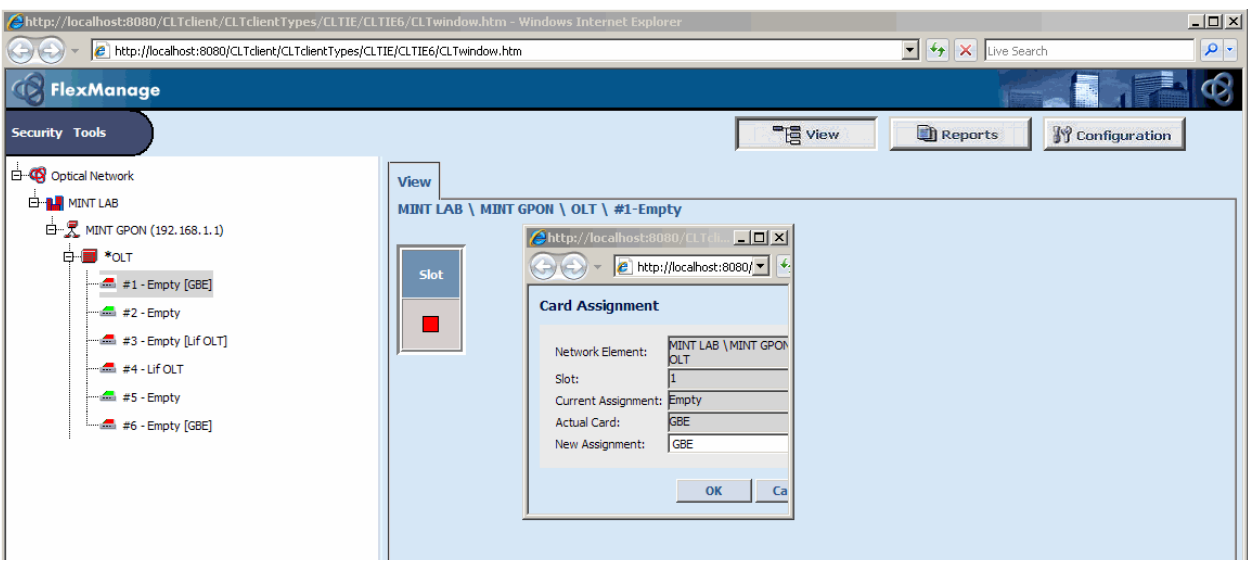


As seen above the Navigation Tree Area is used to reset a card if needed.

The card assignment window contains the following fields:

- Network Element – displays the name and the path of the network element (read only);
- Slot – displays the slot number (read only);
- Actual Card – displays the card installed in the slot as identified by FlexManage (read only);
- New Assignment – select the card type to be assigned to this slot from the pull down menu. The list of cards displayed in the pull down menu varies according to the shelf type.

Remark: slot 4 is reserved for the LIF card and no other card can be assigned to this slot.

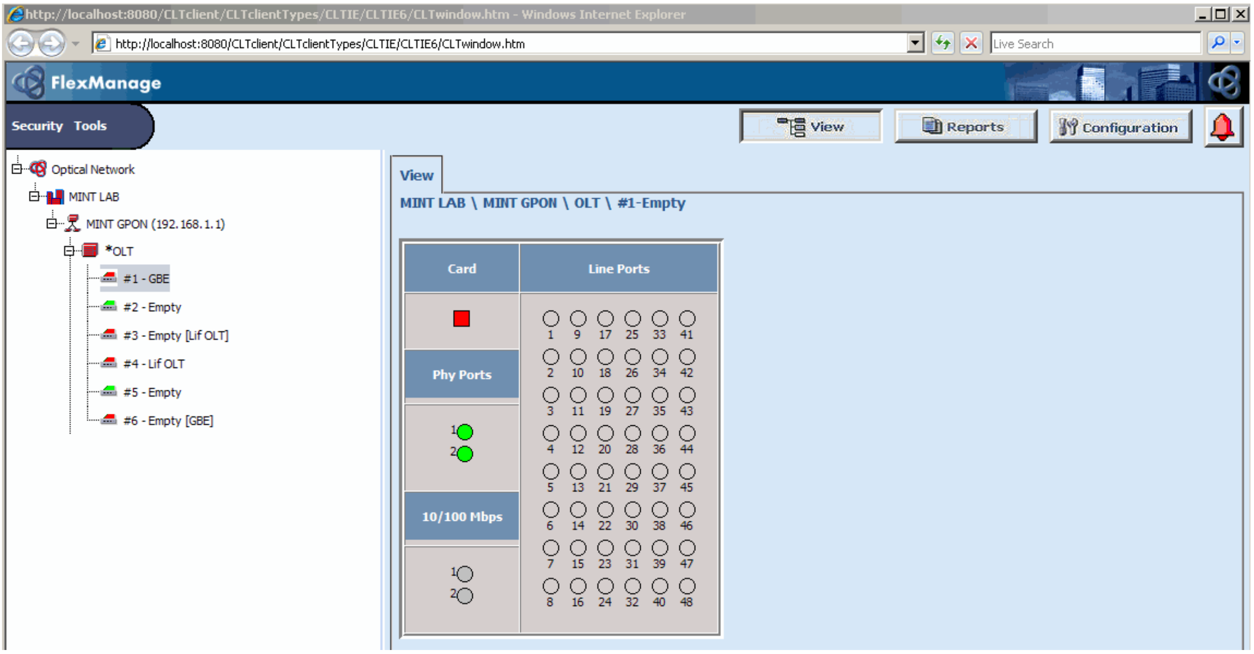


The GBE card has 48 logical ports associated with it:

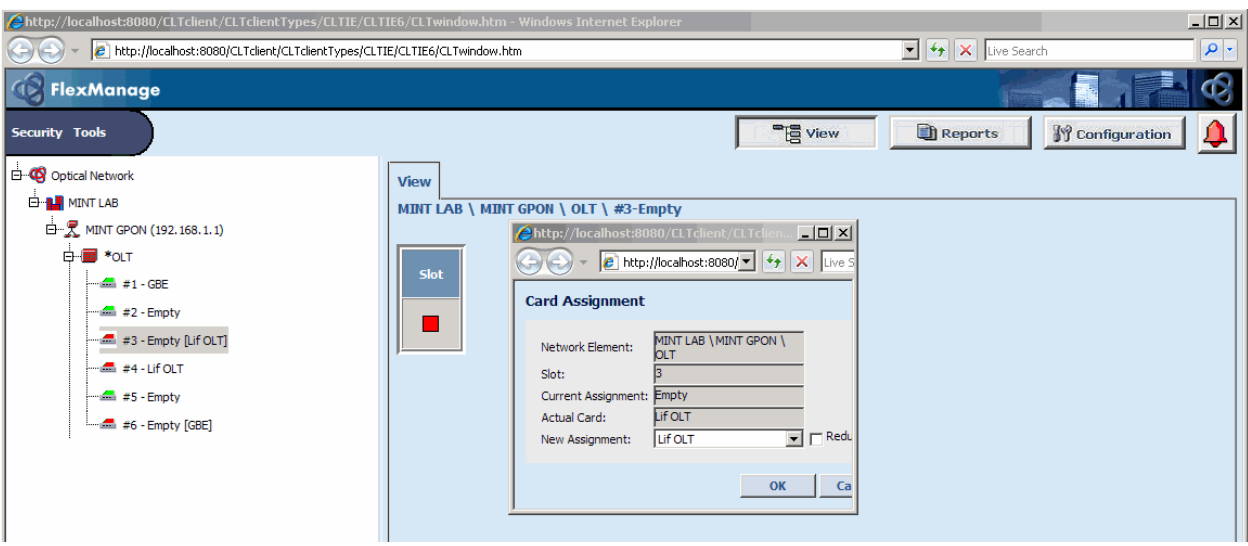
- 1 to 24 for the first GbE port;
- 25 to 48 for the second GbE port.

If the 10/100 auxiliary ports are enabled they are automatically associated with logical ports 1 and 25 (see 4.2.10.). That is why is recommended not to use these logical ports when declaring a trail. Also, this is the reason why the OLT assigns window 2 for the first ONT - see figure 44: [2] RACK1-ONT1 ([2] = transmission window number) or select LIF card slot 4 in View mode.

GBE view card display after successful assignment:



In order for the OLT to support LIF redundancy, PON protection, or dual PON, the shelf must be equipped with a second LIF card. For a dual PON configuration the Redundancy box in the card assignment window has to be left unchecked:



If used for protection, the second LIF card functions as a slave and its downstream transmitter is disabled. In addition to providing the GPON optical functions the main LIF card contains the system controller (CPU). The protect card contains the same processor, but this processor is disabled while in the protect slot.

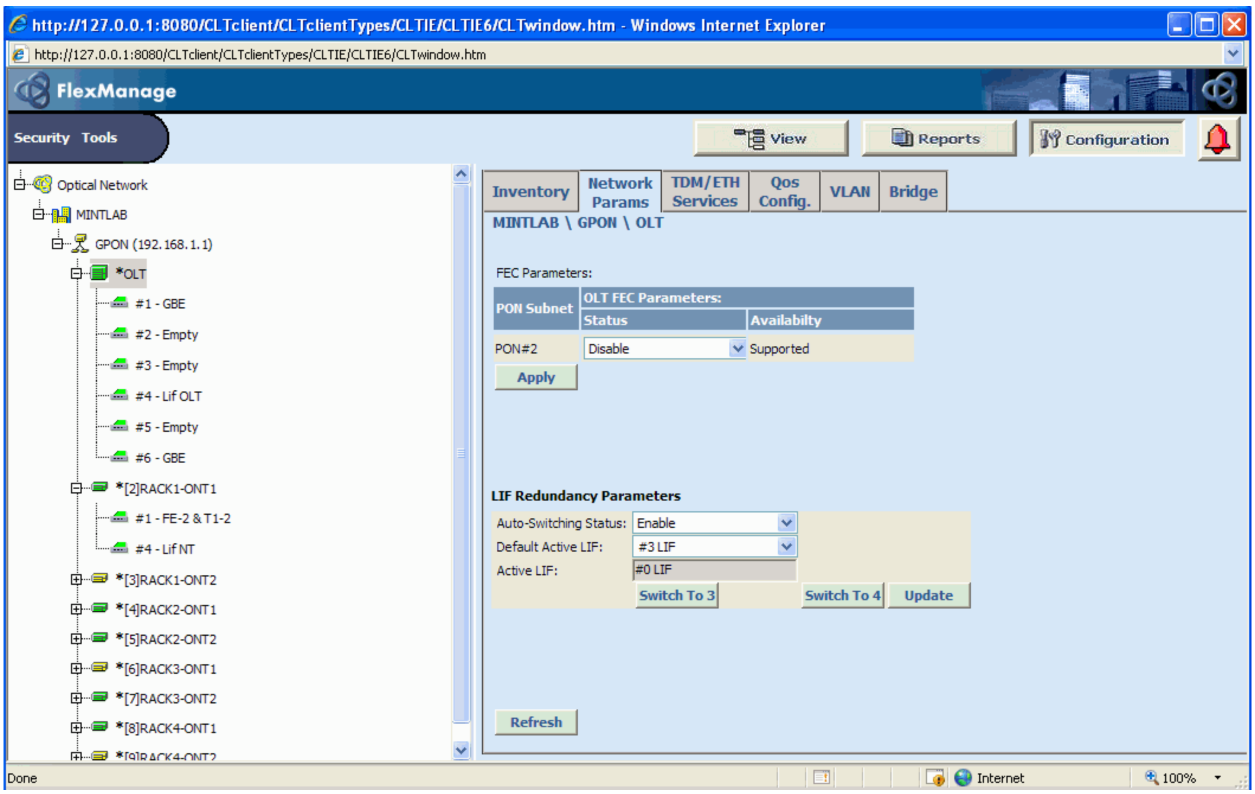
Even if the downstream transmitter is disabled, the protect LIF card still comports as if it was the active module. In parallel with the active LIF, it puts together the full GPON downstream frame and sends it to the optical transmitter. It is also receiving all of the upstream traffic and sends this traffic on the second backplane buss to the CIF cards. The cards are told which LIF card is active, so that they will receive only from the active LIF. The CIF cards also transmit on both buses to the LIF cards, so that all traffic is flowing on both buses at all times. This decreases the overall protection switching time and minimizes the loss of data in the event of a protection switch.

In case of failure in the optical components in the main LIF card, the protect LIF card takes control of data traffic. The main LIF, which contains the CPU, still controls the system OAM functionality. Therefore, the main LIF processor is still active, only the optical and data path have failed.

In addition, both the active and protect LIF cards monitor the upstream integrity and will initiate a protection switch for the following reasons:

1. Receiver detected events:
   - Digital Loss of Signal (LOS) or RX LOS,
   - Loss of Window (LOW) of all operating ONTs,
   - Loss of Framing (LOF) of all operating ONTs,
   - Signal Fail (SF) of all operating ONTs;
2. Transmitter detected events:
   - TX-Bias-High,
   - TX-Power-Low Alarms.

Remark: it is expected that the main LIF would fail first, as its optical transmitter and receiver are used first. Therefore, the CPU and the SW stack are active from the slave LIF. This enables the user to replace the main LIF while the system is running on the secondary LIF, and then manually return the system back to the main LIF.



Remarks:

– PON numbering starts from 2: PON Subnet 1 is not used.
– Before removing a PON card (in order to replace it), verify that this card is not active. When the LIF card is active, its TX LED is green.
– Since the SW stack is located on the LIF in slot 4, before removing it, the database should be backed up. This process will be described later.
– By selecting the Network Parameters tab in the OLT configuration mode the FEC option can be enabled. This results in an increased link budget by approximately 2-3 dB. On the downside, because of the overhead, there is a decrease in BW efficiency.

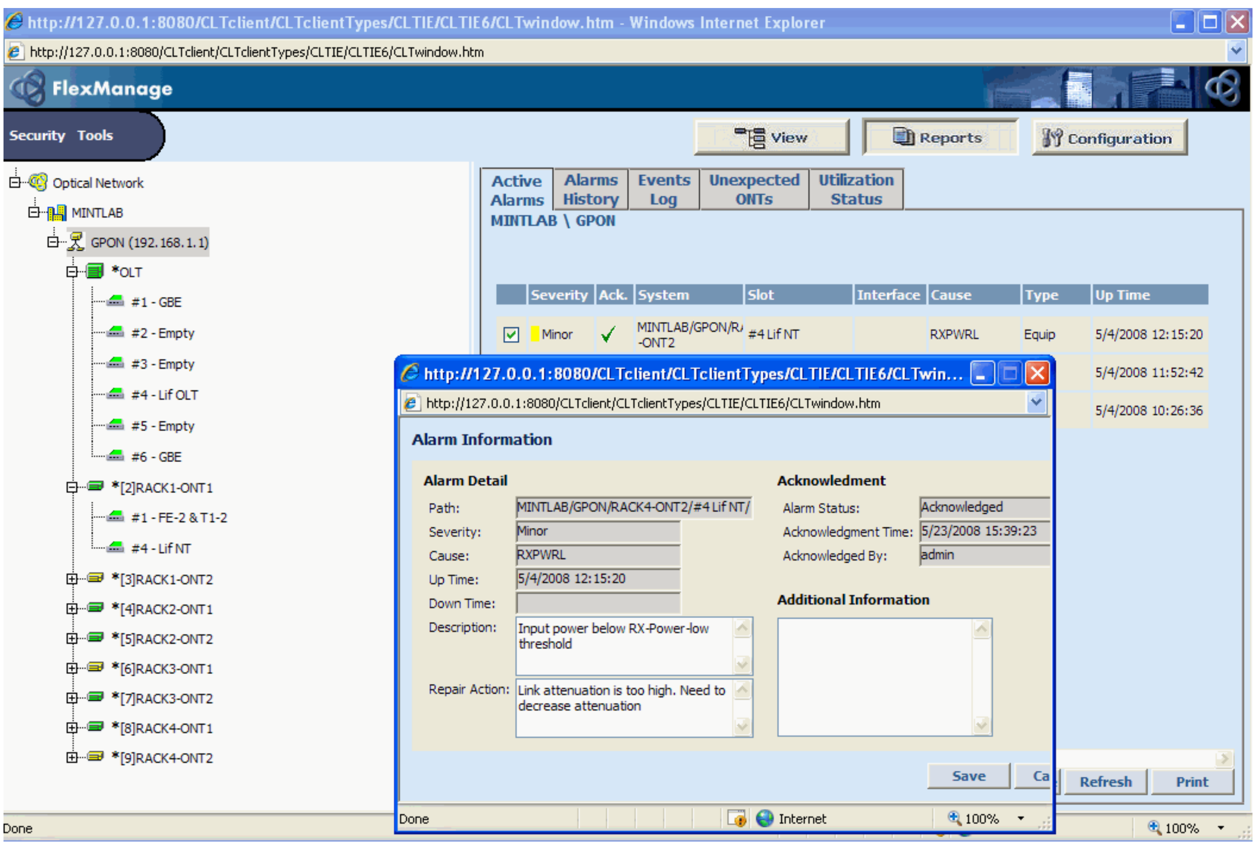
4.3.4. Reports and Alarms Management

The FlexManage reports are filtered based on the hierarchy of the Navigation Tree Area. There are several different types of reports:

- Active Alarms – displays a log of current alarms;
- Alarms History – displays a log of all alarms that have already terminated;
- Events Log – displays a log of all events that occurred in the network;
- Unexpected ONTs – displays a list of ONTs that exist in the network, but are not configured in the system;
- Utilization Status – displays a graphic illustration of the used and available bandwidth per subnet and ONT.

Whenever an alarm occurs on an object monitored by FlexManage, the color code, based on the alarm severity propagates to the parent level of the object. If a minor alarm occurs at the shelf level, the color code of the minor alarm severity (yellow) will propagate to the subnet level and to the site level in the navigation tree.

The Active Alarms list provides a list of all current alarms in the system. Using the Command Buttons a description of the alarm can be displayed, the alarm can be acknowledged or unacknowledged, or the list can be refreshed or printed.



Remark: the reason given in the alarm description showed above is false. The receiving power for all ONT's are well within the limits of the receiver sensitivity – see Table 12 for all power measurements. For example, the power level measured at the RACK1-ONT2 (- 13.1 dBm) is stronger that the one measured at RACK1-ONT1 (-13.3 dBm). If the graphical view of the transmitting and receiving power levels is used the ONT receiving power level displayed (see 4.3.5.) is bellow the receiver sensitivity (- 23.3 dBm for RACK1-ONT2, – 50 dBm for RACK3-ONT and RACK4-ONT2). These ONTs should be replaced (or recalibrated?).

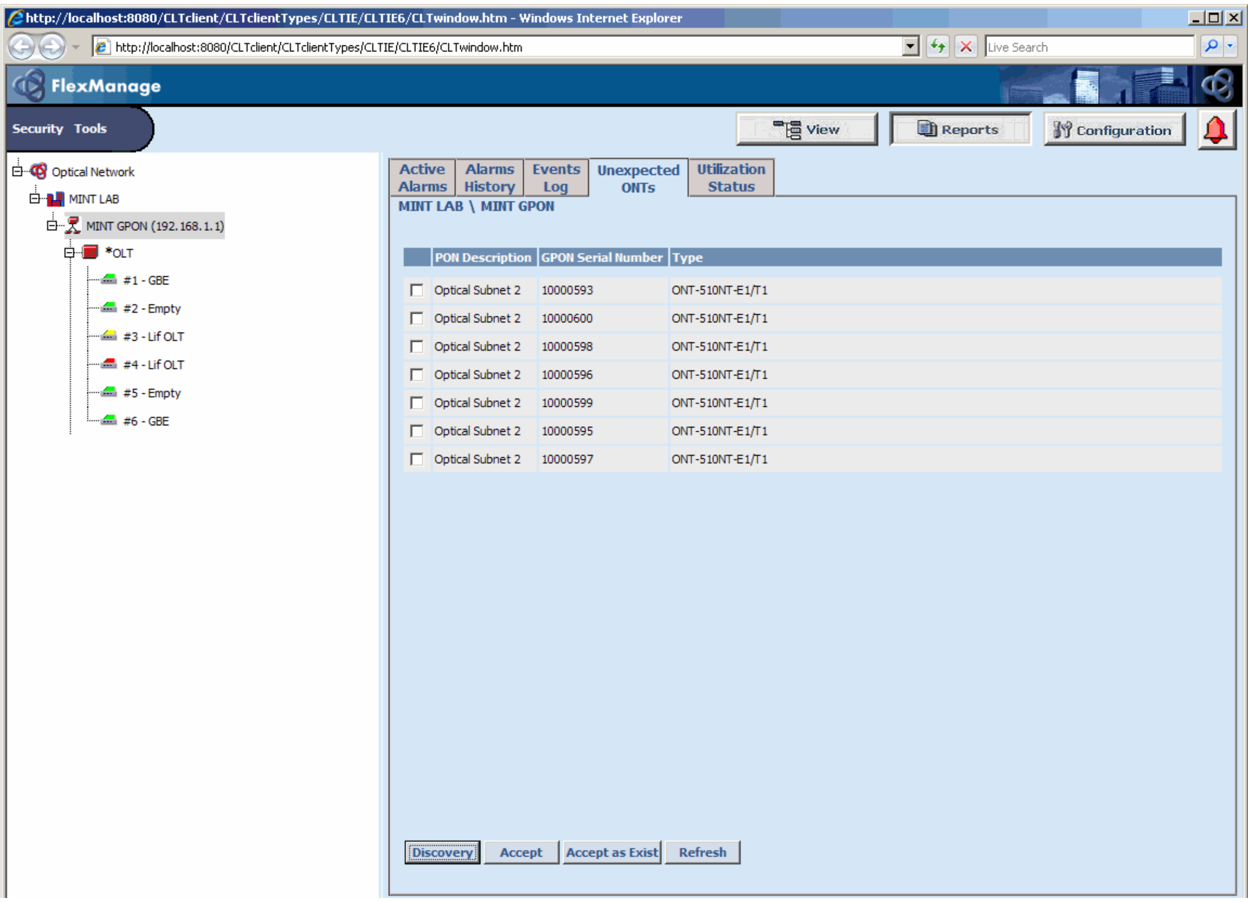
4.3.5. Add an ONT to the existing PON

FlexManage can detect ONTs that exist in the network but are not configured in the system. These ONTs are recognized by their serial number and are displayed in the Unexpected ONTs list, which is presented at the subnet level. For double PON configuration, the list is displayed for each PON.

If an ONT's upstream window is not received at the OLT because of LOS or other malfunction, the ONT is declared 'missing' at the OLT. The OLT periodically searches for all missing ONTs until they are found. The search is not traffic affecting. This search can be initiated manually by using the Discovery command button in the Unexpected ONT's tab.

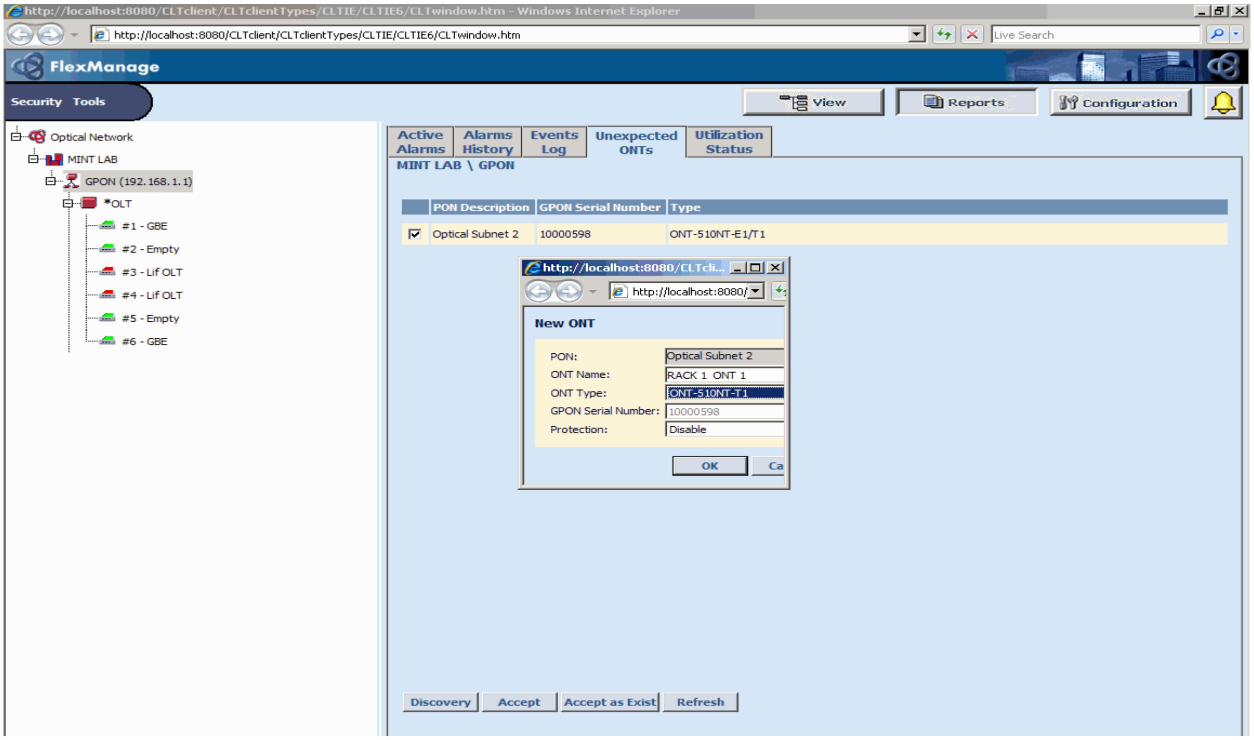
There are two ways to add an unexpected ONT to the system:

- Accept — accept the ONT from the Unexpected ONT list;
- Accept as Exist — take the Unexpected ONT from the list and match's it with a non active ONT.

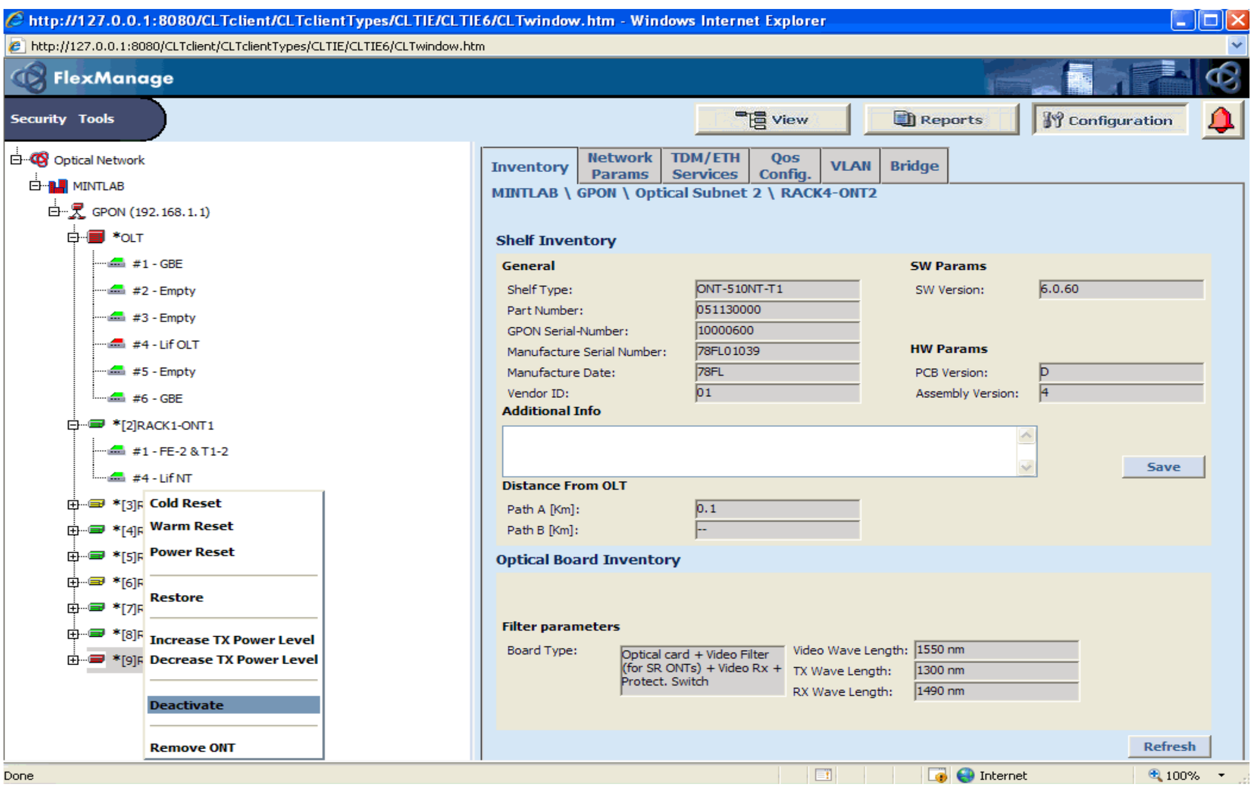


When an ONT is accepted a new window containing the following parameters is displayed:

- PON – the OLT subnet in which the ONT will be added (read only);
- ONT Name – the text entered here will identify the ONT in the Navigation Tree Area;
- ONT Type – select from the pull down menu the type of the ONT installed. There are 2 options for the MINT Lab: 510NT-T1 or 1000NT;
- GPON Serial Number – the serial number of the discovered ONT (read only);
- Protection – select for the pull down menu (Enable / Disable) if protection is used (disabled in the existing configuration).



After the ONT was accepted it is automatically rebooted, ranging is initiated and an equalization delay (EqD) compensating for the distance from itself to the OLT is assigned. Once this process is completed the FlexManage will upload the ONT information in its database and the Navigation Tree Area will be updated. Using the FlexManage distance measured between the OLT and each ONT for both the main and protect path can be retrieved from a dedicated screen:

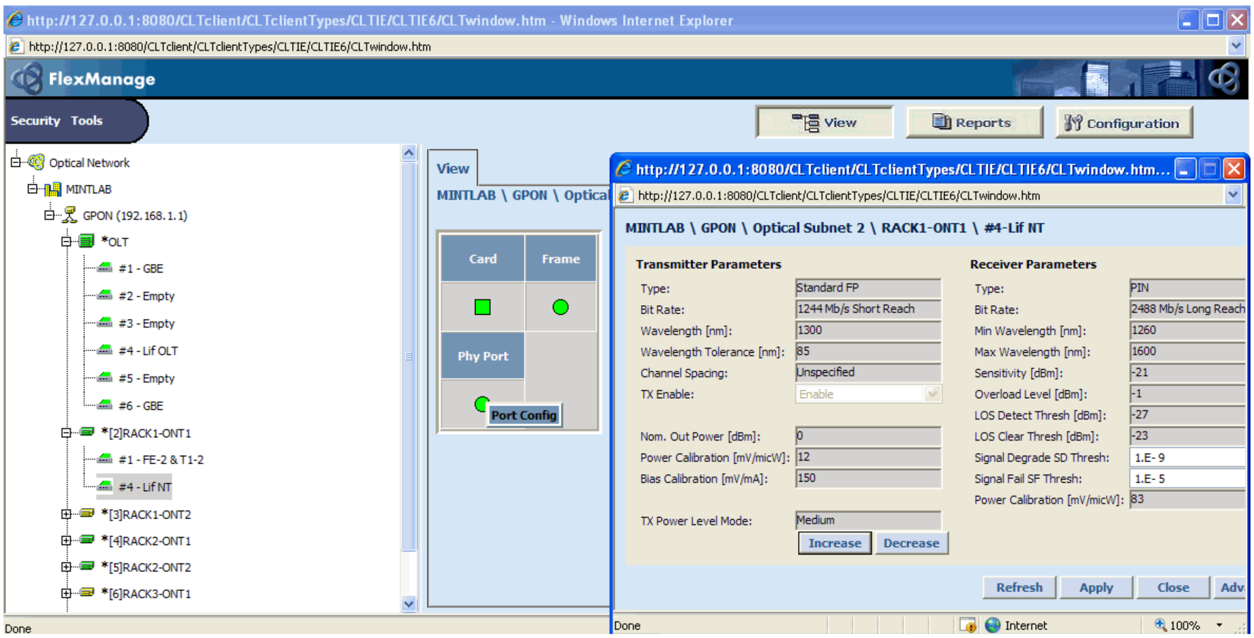


Using FlexManage an ONT can be deactivated at any given time, without affecting the traffic of other ONTs. The deactivated ONT may be reactivated at any time.

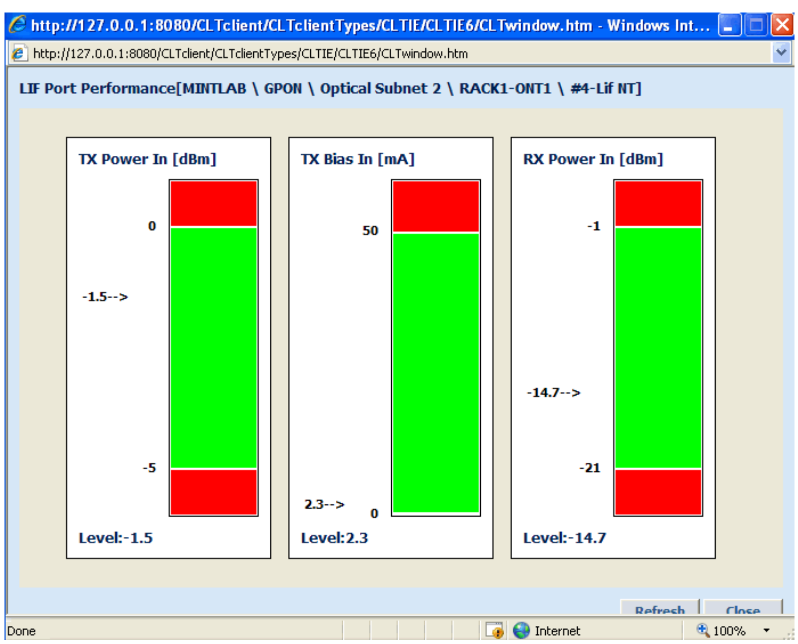
A powering level mechanism allows the user to manually control the TX power of the ONT optical transmitter. 3 optical power levels at 2-3 db differences are supported:

- High (mode 0) - highest transmitted power mode;
- Medium (mode 1) – between high and low power modes;
- Low (mode 2) - lowest transmitted power mode.

This feature increases the dynamic range of the PON network allowing ONT that are close to the OLT to transmit in less power thus eliminating the need to add attenuation in the OLT that will harm ONTs that are located far away from the OLT.



By selecting the advanced button in the screen above a graphical view of the transmitting and receiving power levels is displayed.

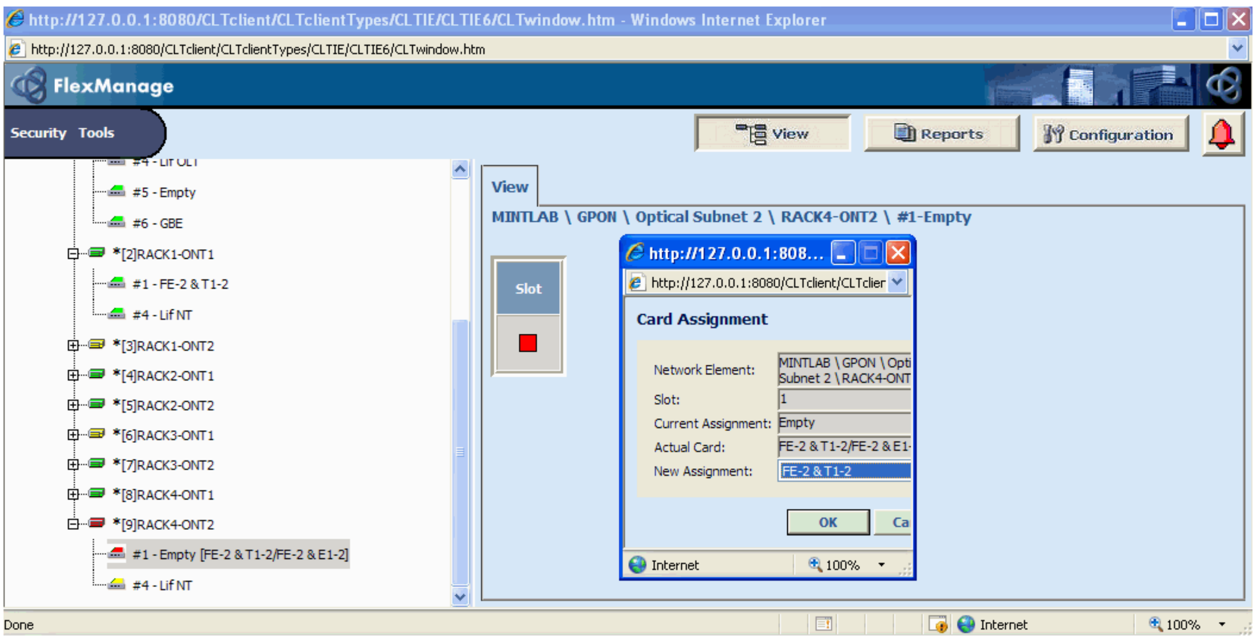


Remarks: the difference of 1.4 dBm between receiving level shown and the one measured with the power meter (see table 12) is due to the ONT internal loss.

If the fiber protection is used then the protection parameter displayed during the ONT acceptance process must be enabled. In the event that the fiber between the OLT and the ONT is broken, the ONT automatically switches in less than 50 ms to the protection path and traffic is resumed. Only those ONTs affected by the fiber outage are affected by this protection switch. The ONT will also automatically switch to the second fiber path for the following reasons: LOS, LOF, and SF.

The combination of using a passive splitter at the OLT and automatic protection switching at the ONT enables the ONT to protection switch independently of the OLT. Since the OLT only needs to switch in case of LIF failure, this greatly reduces the system complexity. During installation of the ONT, the system automatically ranges the ONT on both paths of the network. The fact that the ONT saves the EqD value for each path and uses this in the event of a failure decreases the time to protection switch between the paths.

The card assignment process must be followed before the ONTs are becoming operational:



For each ONT different SD and SF threshold levels can be implemented by configuring the LIF physical port in the view mode. The default values and the range for each one are as following:

- SD – default is 10^{-9} , range: 10^{-9} - 10^{-5};
- SF – default is 10^{-5}, range: 10^{-7} - 10^{-4}.

These thresholds can be implemented at the PON level by entering the desired values in the OLT LIF card.

Remarks:

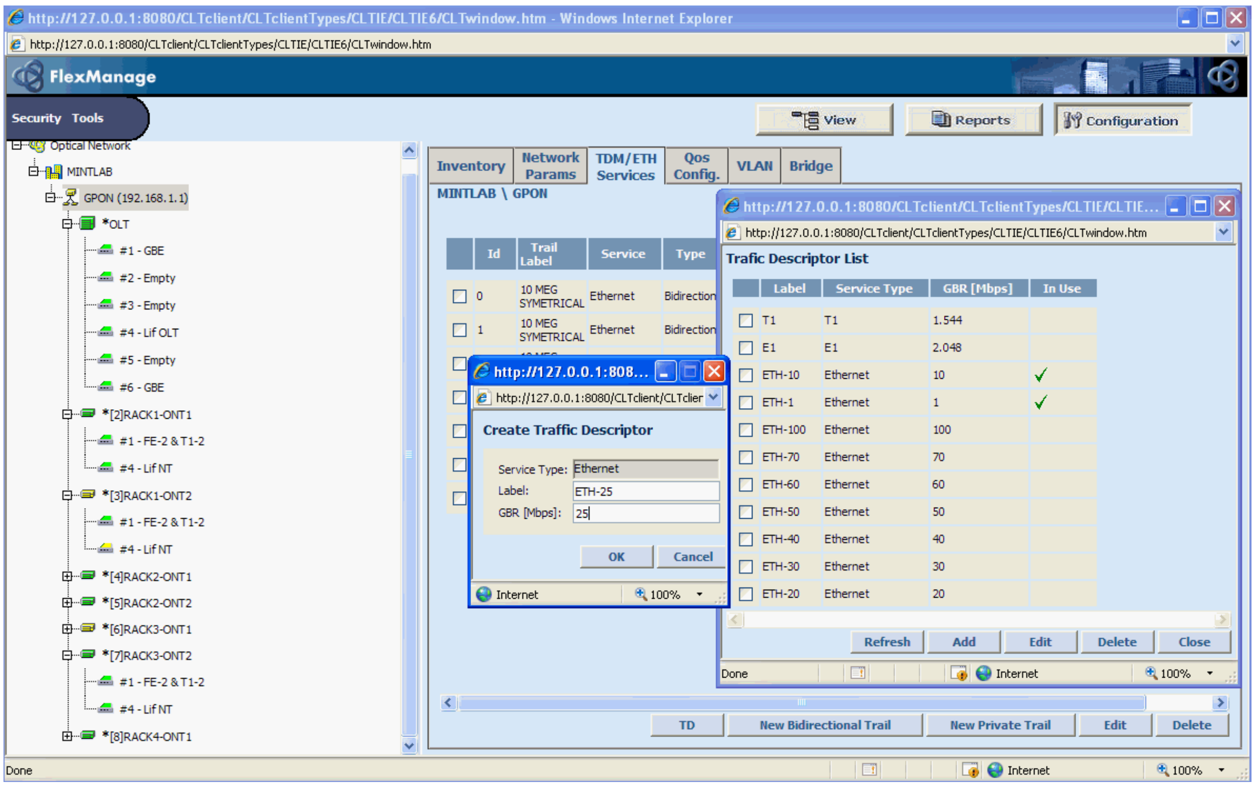
- The 1000NT can be equipped with up to three cards;
- If there is more than one ONT in the unexpected ONTs list they will have to be accepted one at the time;
- It is recommended not to accept an ONT until the previous accepted one is in operational state;
- An automatic dynamic ranging correction process is implemented at the OLT. If the ONT window starts to “drift” from its expected arrival position, the OLT automatically fixes its EqD so the ONT returns to its normal arrival position;
- SD and SF are asserted in the cases where high BER exists;
- The ONT fiber protection feature was not tested.

4.3.6. Add Services - Trails

The service configuration is managed at the subnet level in the configuration mode and by using the desired traffic descriptor.

The Traffic Descriptor defines a profile for handling traffic and is based on the Guaranteed Bit Rate (GBR) – the average data rate. The data rate is the total data rate required for the specific service.

Some default Ethernet traffic descriptors are available for the following bit rates: 20, 30, 40, 50, 60, 70, and 100 Mbps. If other bit rate is needed a new traffic descriptor can be added (or an existing one can be edited). To do this a label identifier and the desired average bit rate have to be entered in the Create Traffic Descriptor window:

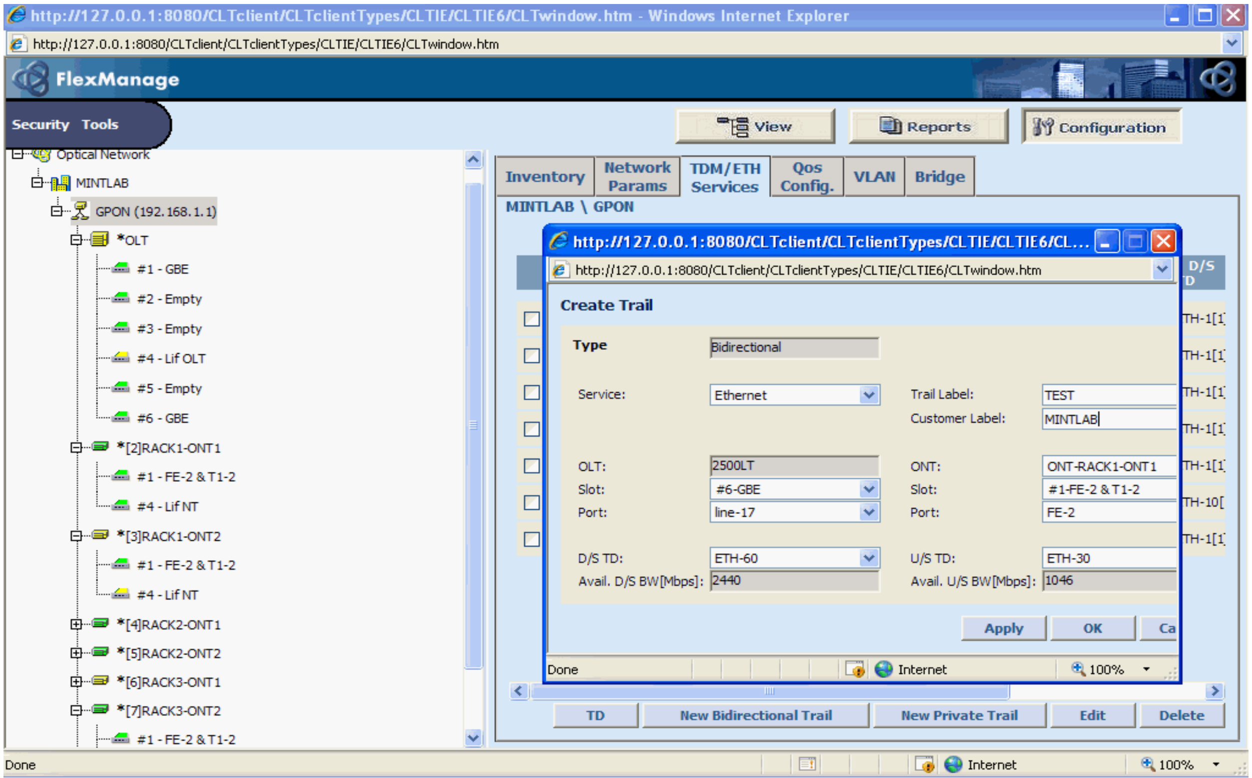


To add an Ethernet service to an ONT port a "trail" must be created. A trail is used to transmit a service from a port in the OLT shelf to a port on the ONT shelf. The trail defines the end-to-end connection and it is composed of a cross-connection in the OLT channel and a cross-connection in the ONT.

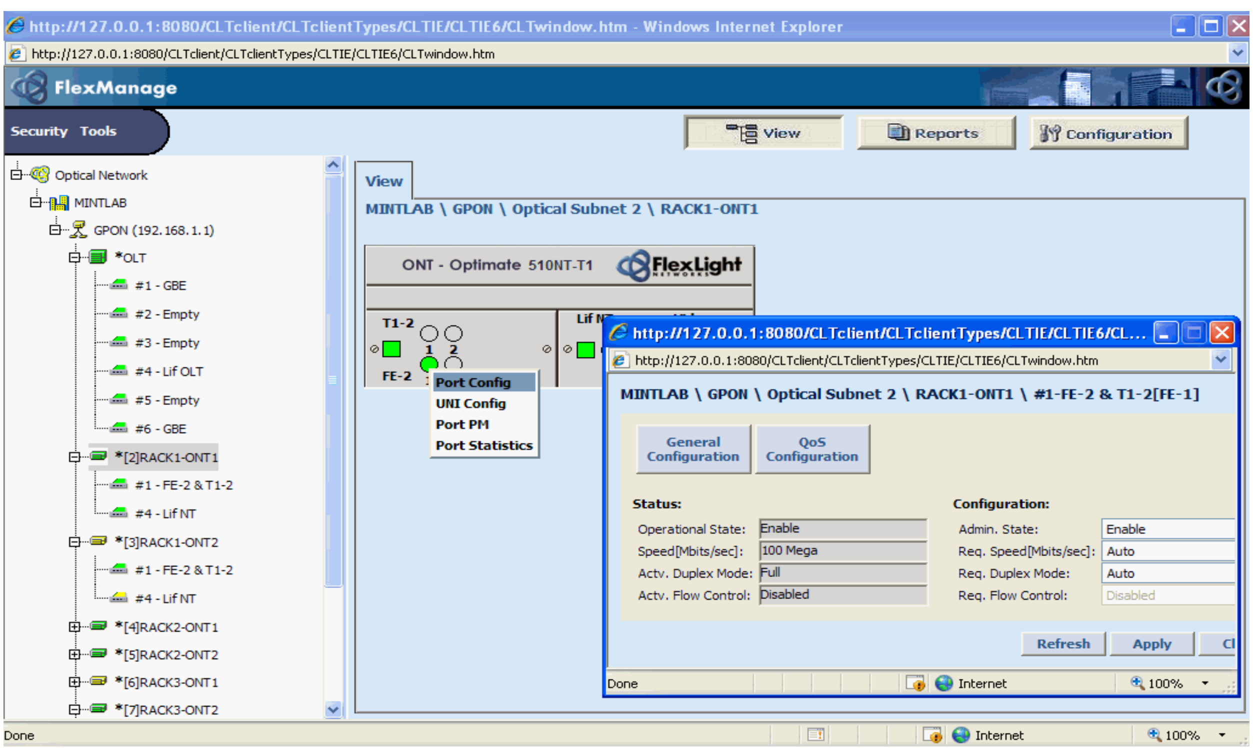
An explanation is given bellow for the parameters needed to set up an Ethernet trail:

- Type – type of trail to be created (read only). The only possible value is bidirectional;
- Service – trail service type. Possible values are T1, E1, and Ethernet;
- Slot – the card on which the trail's end-point is to be configured. Only slots containing cards that match that service type will appear;
- Port – the port on which the trail's end-point is to be configured. The drop-down menu displays only the ports that match the service type;
- D/S TD – downstream traffic descriptor for the trail. The drop-down menu displays only the traffic descriptors that match the service type;
- Avail. D/S BW [Mbps] – the available downstream bandwidth (read only);
- Trail Label – the name for the trail to be created;
- Customer Label – name of the customer for which the trail is created;
- ONT – select the end-point ONT;

- U/S TD – upstream traffic descriptor for the trail. The drop-down menu displays only the traffic descriptors that match the service type;
- Avail. U/S BW [Mbps] – the available downstream bandwidth (read only):



In order to accept traffic the ONT port must be enabled:



From the port configuration window the following parameters can be changed if necessary:

- Req. Speed [Mbps] – Ethernet connection speed:
  - Auto – Ethernet speed negotiated,
  - 10 Mega – Ethernet speed 10 Mbps,
  - 100 Mega - Ethernet speed 100 Mbps;
- Req. Duplex Mode – Ethernet duplex mode:
  - Auto – duplex mode negotiated;
  - Half – half duplex mode;
  - Full – full duplex mode.

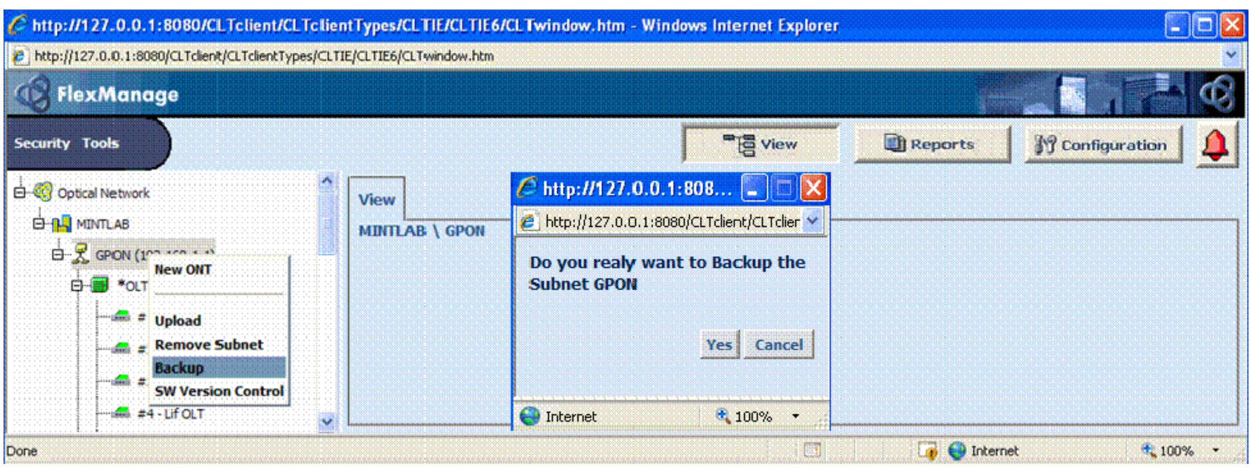
Remarks:

- The T1 and E1 trails use a default traffic descriptor that cannot be deleted or modified;
- A private trail is based on two trails between the two ONT E1/T1 ports and two matching internal ports in the OLT;
- The Ethernet traffic descriptors have a 1 Mbps granularity;
- A traffic descriptor that is in use cannot be edited;
- If the ONT FE port is enabled but no traffic is received a Link Down alarm is propagated through the subnet;
- Only T-CONTs type 1 and 2 are implemented in the FlexLight GPON solution. Type 1 is used for TDM traffic and type 2 for Ethernet traffic. There is no DBA mechanism implemented.

4.3.7. Backup and Restore

Database Backup & Restore refers to the ability of FlexManage to maintain the information of each FlexLight network node.

A user with appropriate configuration capabilities can backup the configuration of all the shelves in the subnet in the management system. The backup operation is only available in the subnet layer. However, when activated, it applies to all shelves (OLT and ONTs) where the backed-up database differs from the current configuration of the equipment. The operation is applied over the entire subnet, and synchronizes the backed-up database for all shelves in the subnet.

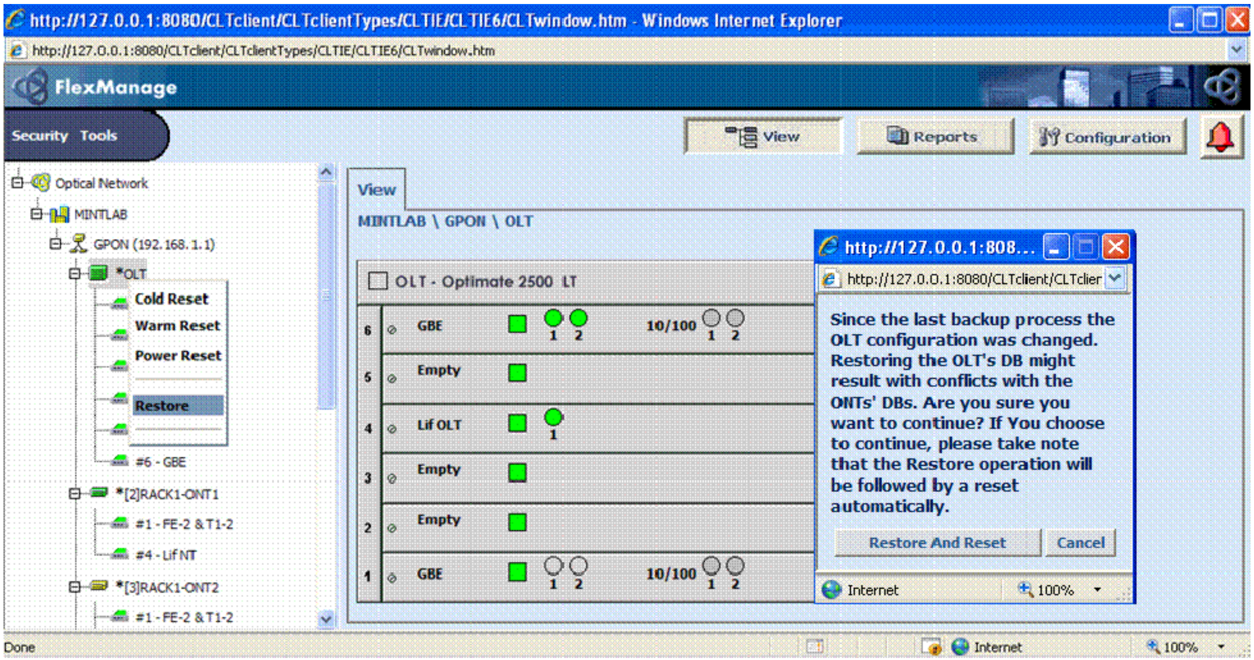


The backup configurations can be restored when necessary; for example if a shelf is replaced due to a malfunction.

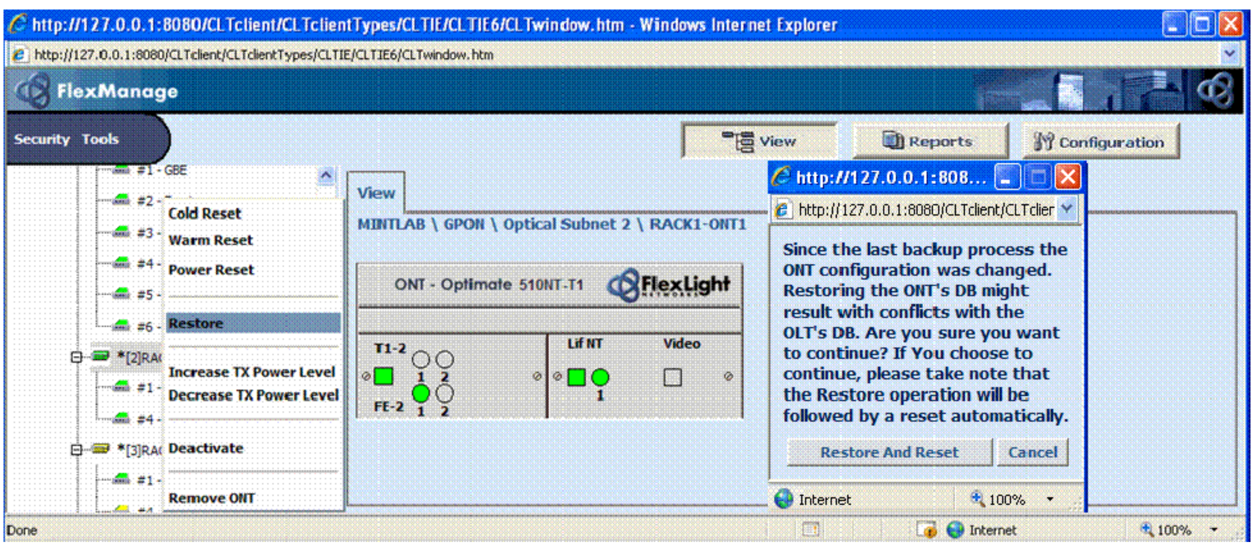
The restore operation restores the configuration of the shelf to the configuration that was in effect during the last backup operation. It is necessary to reset the hardware in order to complete the restore operation.

When a database is restored, the hardware is automatically reset by the management system once the restore operation has been completed.

Restoring an OLT shelf:



Restoring an ONT shelf:



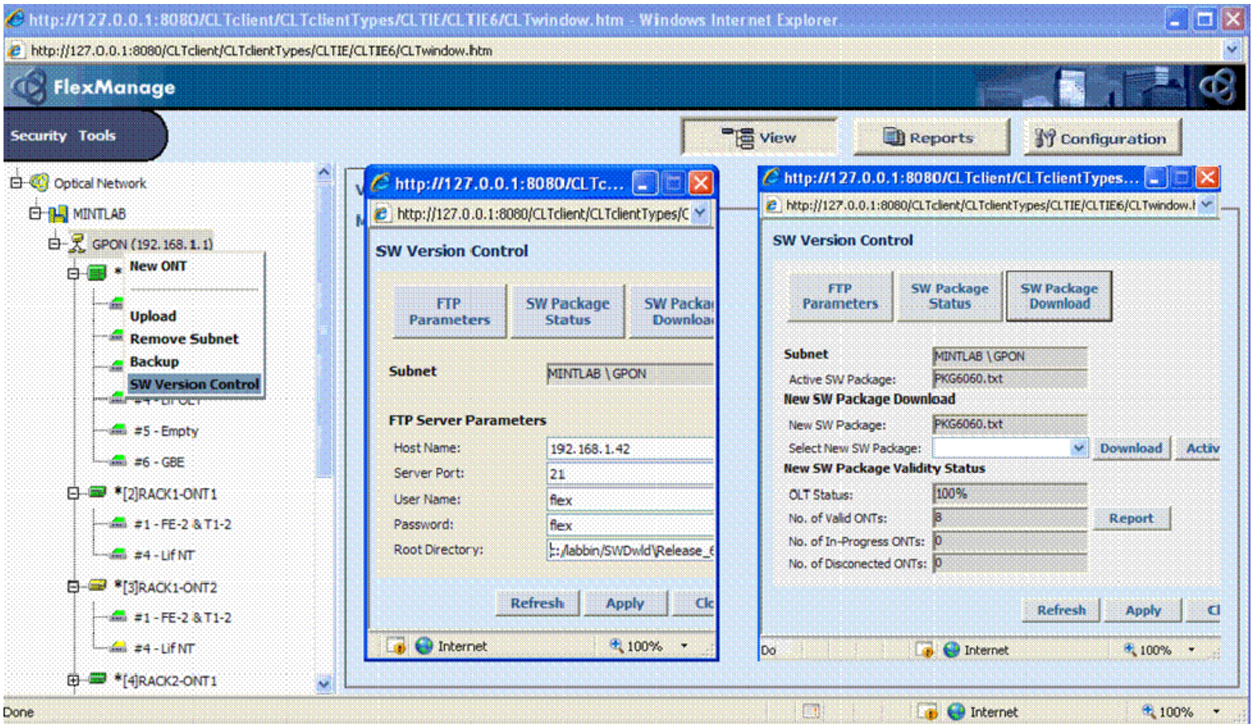
A user with appropriate configuration capabilities can download and upgrade the software to any network component (shelf, card, etc.) if the component is capable of updating or converting the database to the new format required by the software.

Before updating or overwriting the current software, a backup copy of the existing software is created. If the OLT or ONT fails to activate for any reason, the system reverts to the last known good Software Version Control Package. This is an automatic process and no user intervention is required.

A software package includes all the software and hardware files and versions that are required for a network component. An entire subnet (OLT and ONTs) can be upgraded using a single software package.

The download process does not affect traffic and the upgrade process only affects traffic on certain cards for a short period of time when it is necessary to reset the hardware.

Before proceeding with the download, the FTP Server Parameters must be configured:



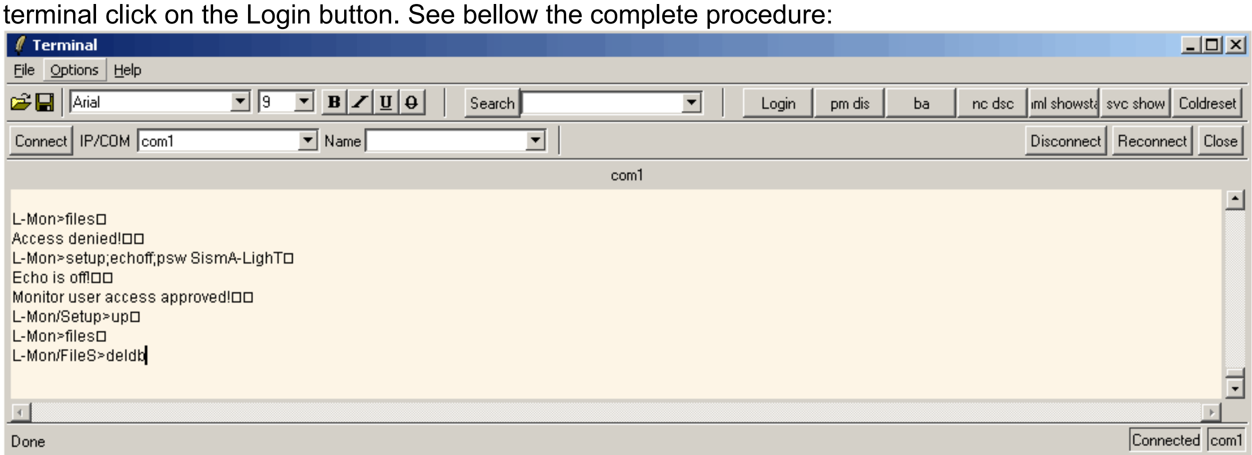
The SW Package Download section is used to start the download process and to activate the new software package.

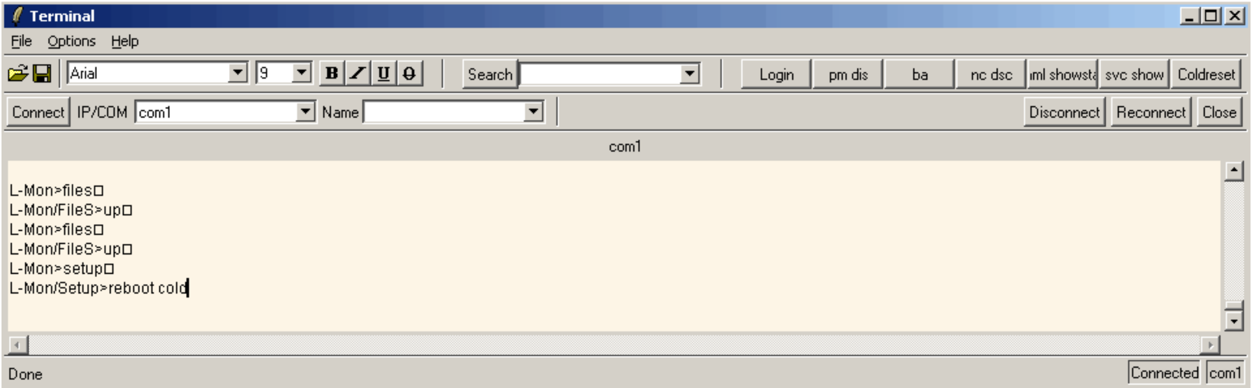
Once the software download has been completed and the status of the OLT is valid, the new software package must be activated. Once the activation is done the name of the new software package replaces that of the software package in the Active SW Package field.

4.3.8. Deleting the OLT / ONT Database

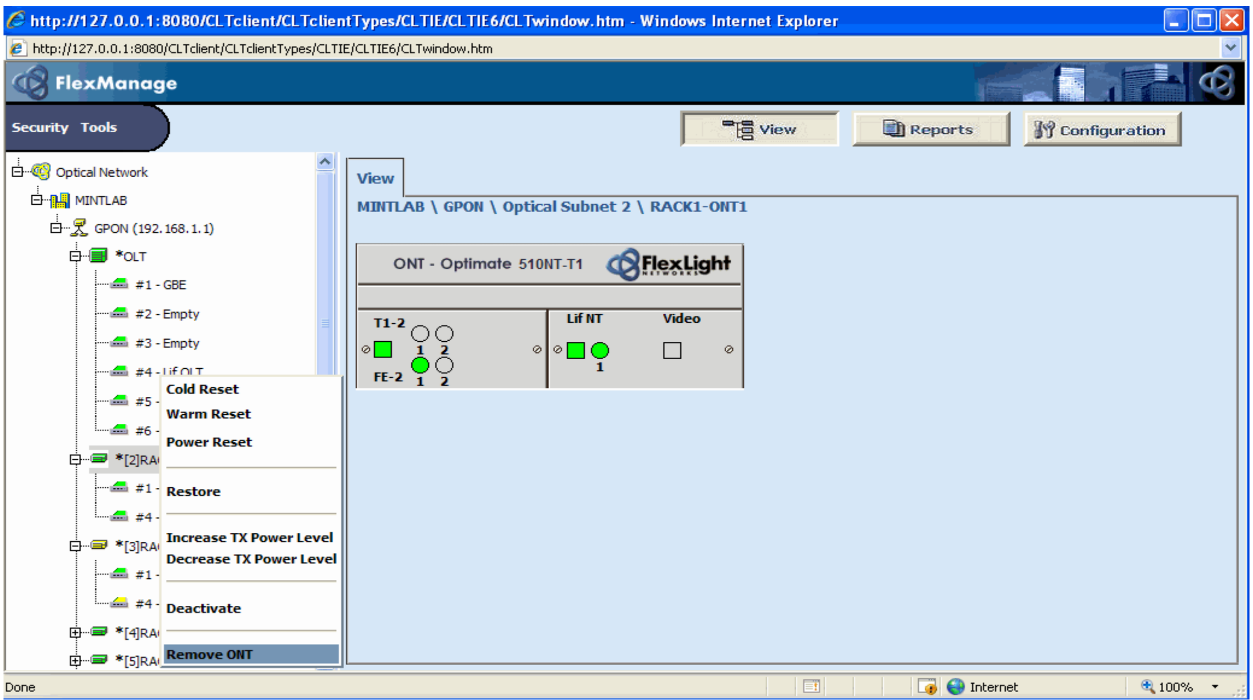
If the OLT or ONT internal database is corrupted the Terminal application can be used to delete it. A power reset or "reboot cold" CLI command needs to be performed to complete this process.

In order to delete database full user access rights are needed. To obtain them the following set of commands must be entered in the Hyper Terminal application: "setup;echoof;psw SismA-Light"; for the terminal click on the Login button. See bellow the complete procedure:

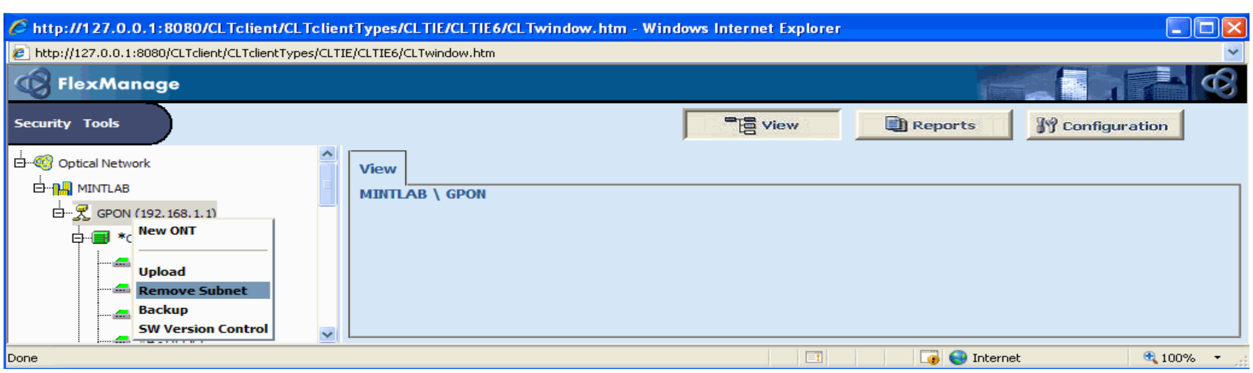




If the ONT database is deleted it must be also removed from the FlexManage subnet and then rediscovered:



For the OLT the entire subnet must be removed from the FlexManage:



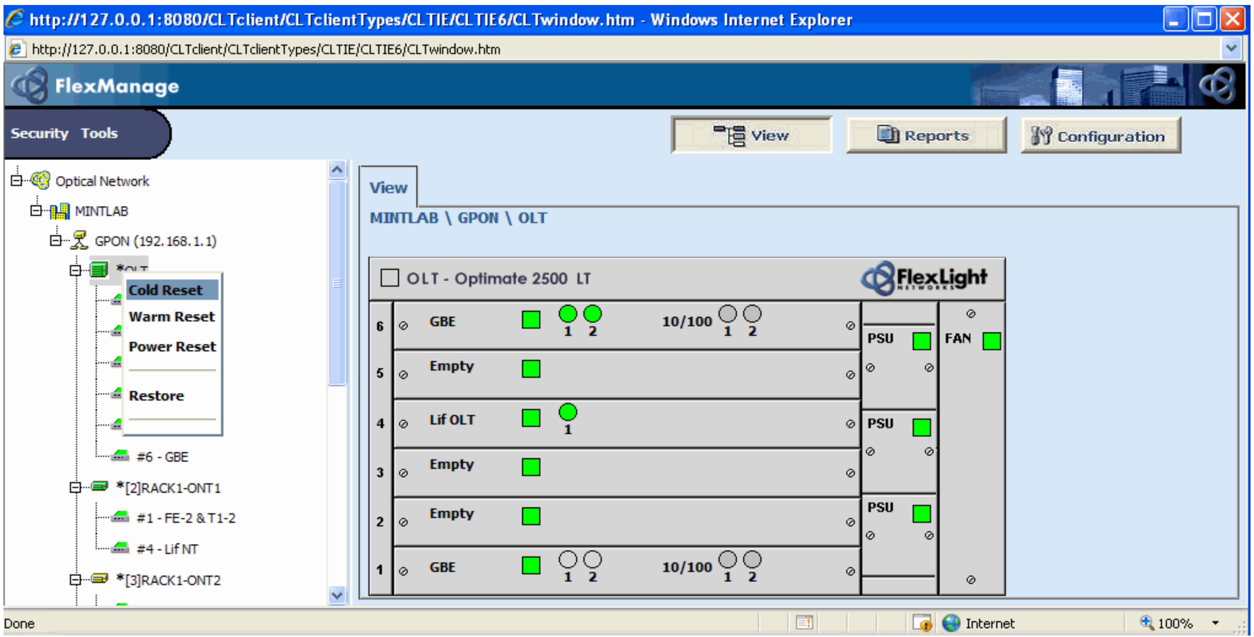
Remark: this procedure must be followed if the PON configuration is changed to dual PON or vice versa.

4.3.9. Resetting Commands

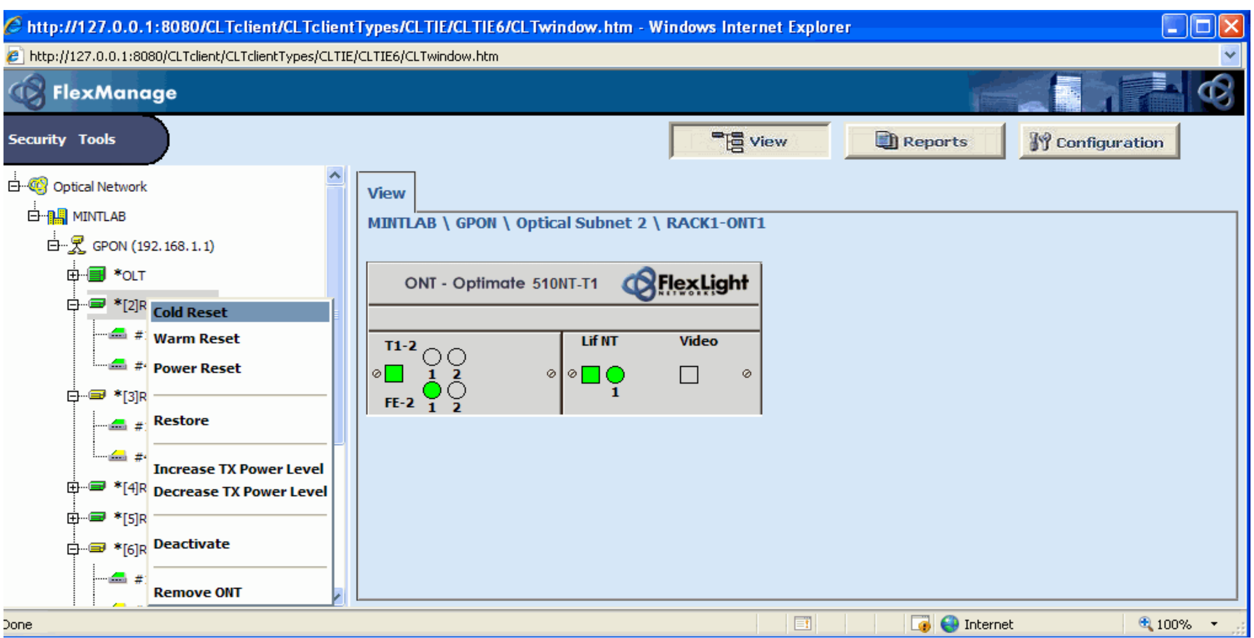
To perform a shelf reset, right click on the shelf in the Navigation Tree Area. The following reset commands are available:

- Cold Reset – hardware reset;
- Warm Reset – software reset;
- Power reset – resets the power supply unit.

FlexManage OLT reset window:

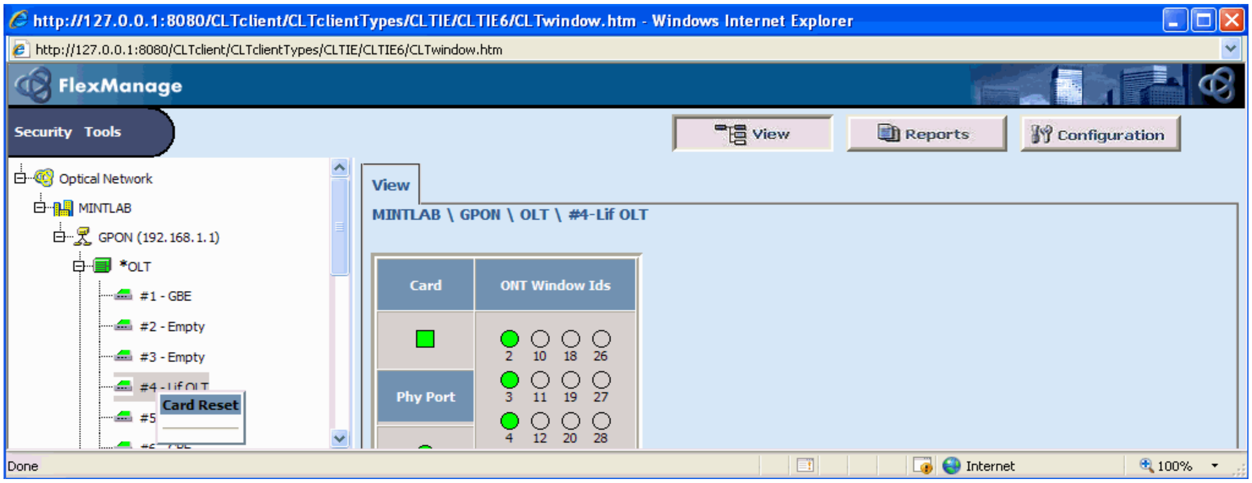


FlexManage ONT reset window:



Remark: by selecting the Increase or Decrease TX Power Level commands the ONT power mode (see 4.3.5.) can be changed.

Te reset a card right click on the selected card in the Navigation tree area:



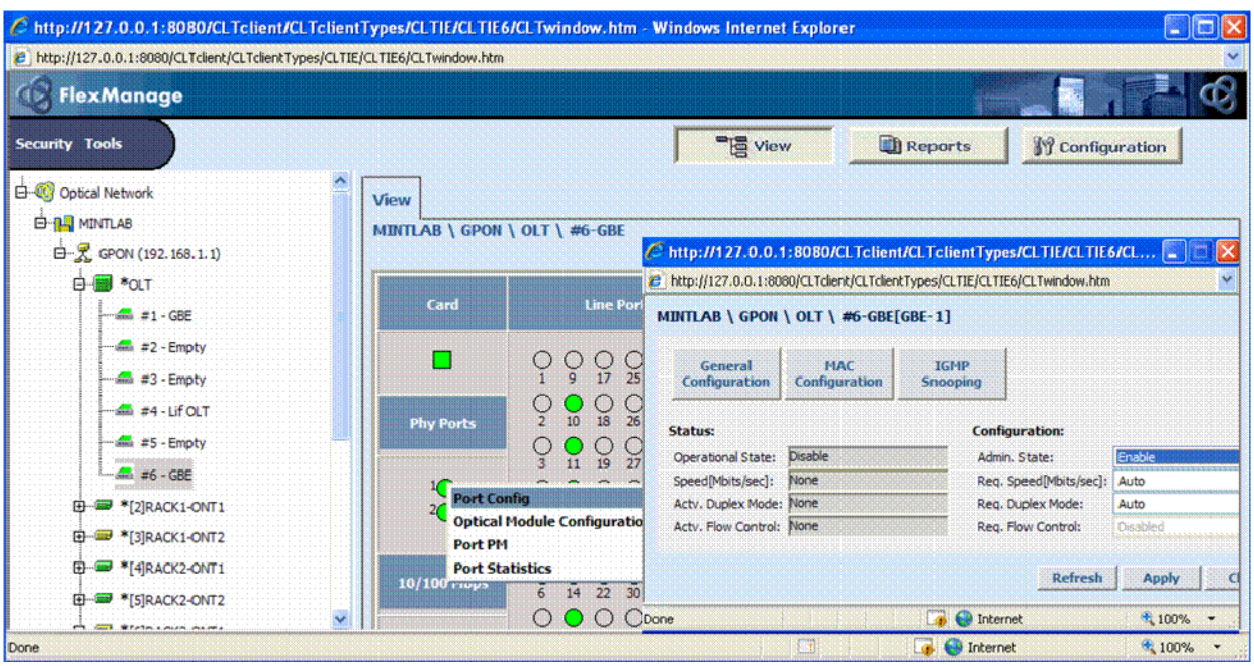
4.3.10. Uplink Ports Configuration

The GBE is the OLT Ethernet Interface card. The GBE Card incorporates an Ethernet Bridge (Layer 2 switch). The Bridge configuration concentrates the traffic from all end clients connected to the ONTs to one or two uplink GigE interfaces. A dual GbE uplink can provide not only the bandwidth capacity of two Gigabit Ethernet ports but also a failover capability to overcome uplink port, fiber or equipment failure.

Being a L2 Bridge, the GBE card forwards Ethernet packets between the various ports (FE line ports and GbE uplink ports) based on the MAC address table under MAC & VLAN port membership constrains.

The GBE card supports two GigE interfaces (Phys Ports) and 48 Logical Fast Ethernet Internal Ports (FE line ports).

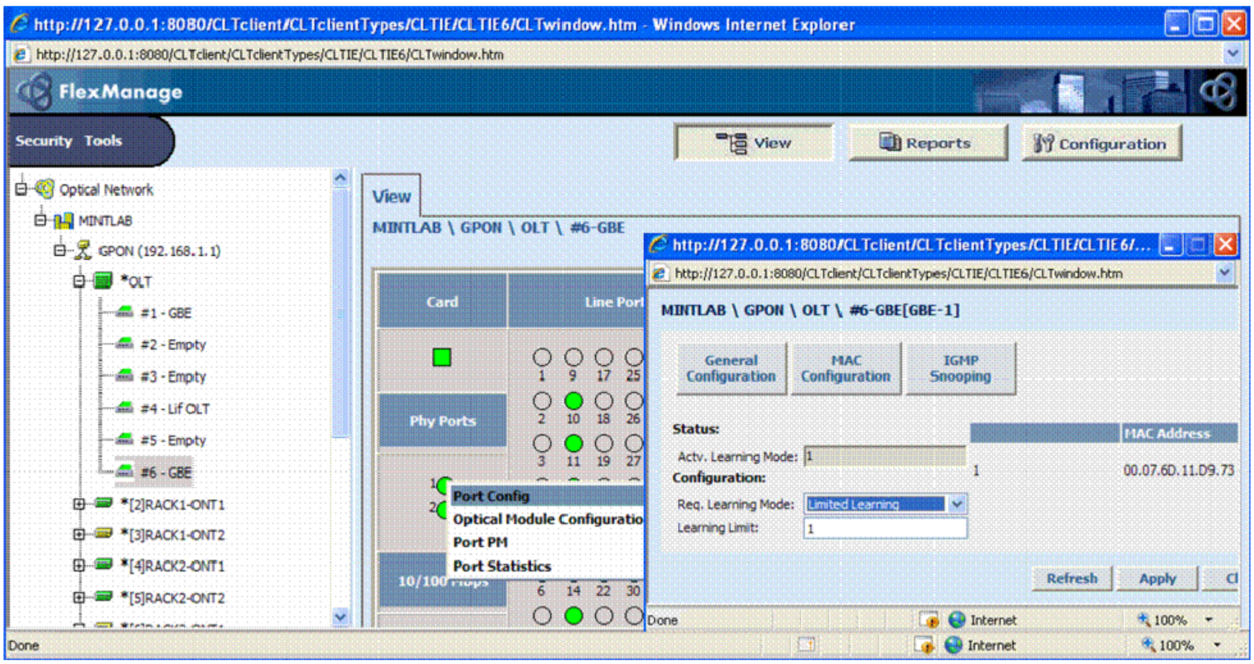
Use FlexManage as illustrated bellow to enable a GbE uplink port:



The following parameters can be configured:

- Admin. State – select the administrative status:
  - Enabled,
  - Disabled;
- Req. Speed - Ethernet connection speed:
  - Auto,
  - 1 Giga;
- Req. Duplex Mode – Ethernet duplex mode:
  - Auto,
  - Full.

Every incoming packet triggers a source MAC address learning process in which unicast MAC addresses are learned, which means the packet source resides behind the port through which the packet was received.

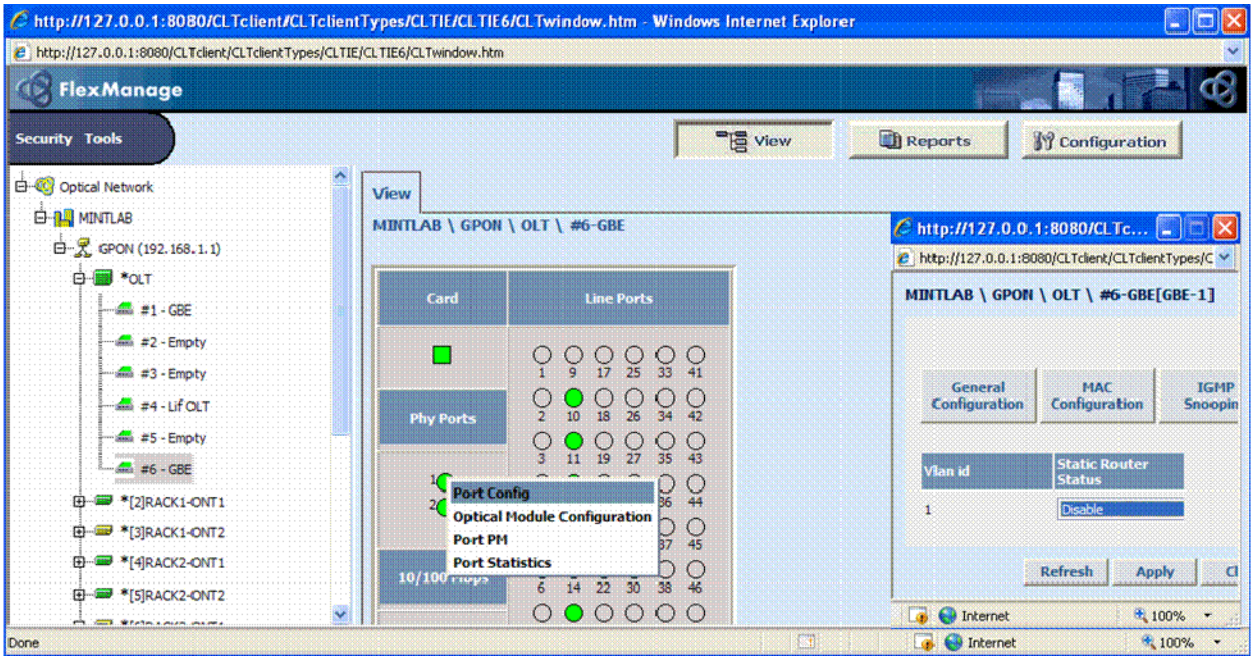


In the Ethernet port MAC Configuration window the learning mode can be selected for Req. Learning Mode parameter:

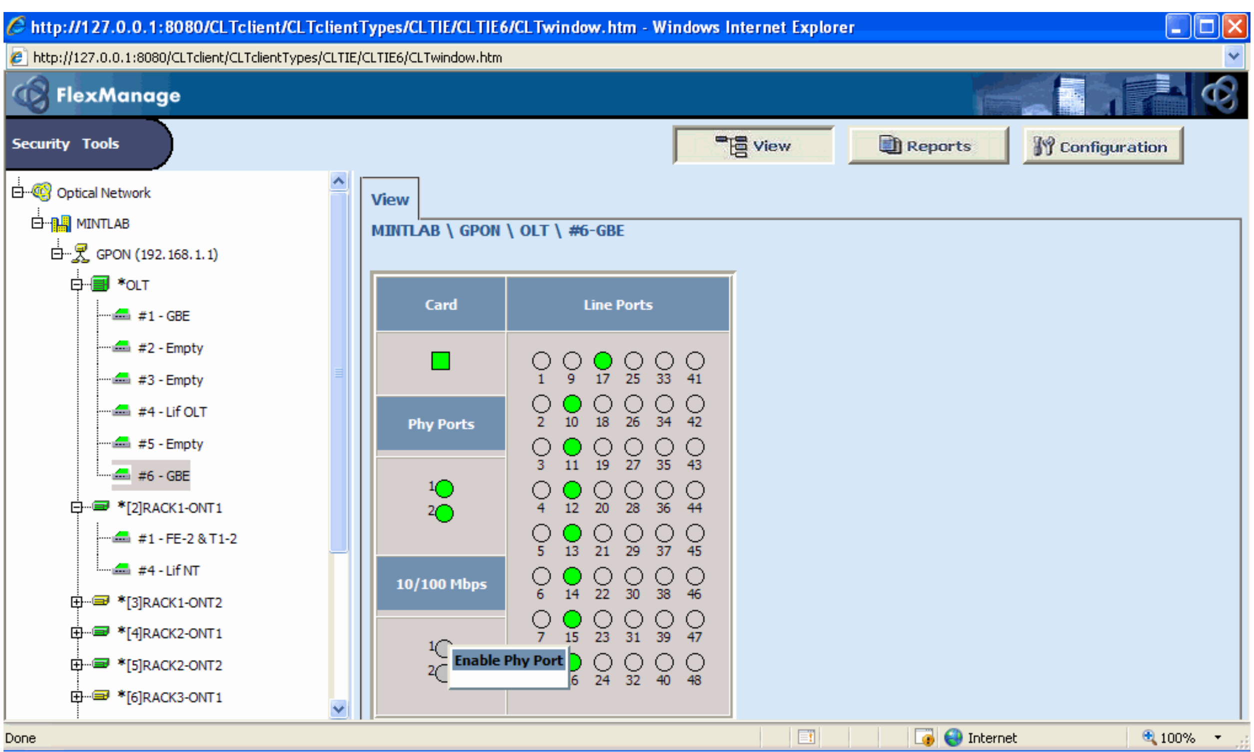
- Unlimited – learns all MAC addresses mapped for this port,
- Limited - learns a limited number of MAC addresses. When this option is selected, the Learning Limit field is displayed. Enter the exact number (up to 15) of addresses to be learned. When there are more than 15 addresses mapped, old addresses are erased from the database, allowing new addresses to be learned.

Internet Group Management Protocol (IGMP) is used by IP hosts to dynamically register to an IP multicast group by sending registration messages to their local multicast router. Under IGMP, routers listen to IGMP report messages and periodically send out queries to discover which groups are active or inactive on a particular subnet. IGMP snooping intends to limit the IP multicast forwarding only to those ports through which an IGMP join request has been issued. Normally a Bridge forwards IP multicast frames, identified by specific MAC group address, to all ports on the same VLAN. Such behavior would normally result in unnecessary bandwidth consumption on ports that did not “ask” for (join) the flow. To avoid this phenomenon, the Bridge blocks all IP Multicast frames, unless an IGMP join request is issued from any of the ports asking to join the group of listeners of a specific IP MAC group address, in which case a bridge multicast forwarding table is updated such that IP multicast forwarding is done only towards those ports that asked for specific multicast flows. IGMP protocol runs between hosts and routers and between routers and their next hop peer routers. The Bridge listens to the IGMP join and leave requests learning which port asks to join or leave and which group address. As it keeps track of group address listeners it updates the multicast forwarding table accordingly upon every change in the group membership.

IGMP can be enabled / disabled in the IGMP Snooping window displayed when the Port Config option is selected in the View mode:



The GBE includes 2 separate auxiliary 10/100 Mbps ports which, unlike the GbE ports, are not enabled by default.



The only differences in the parameters settings for 10/100 ports comparing with the GbE are:

- Req. Speed - Ethernet connection speed:
  - Auto,
  - 10 Mega,
  - 100 Mega;
- Req. Duplex Mode – Ethernet duplex mode:
  - Auto,
  - Half,
  - Full.

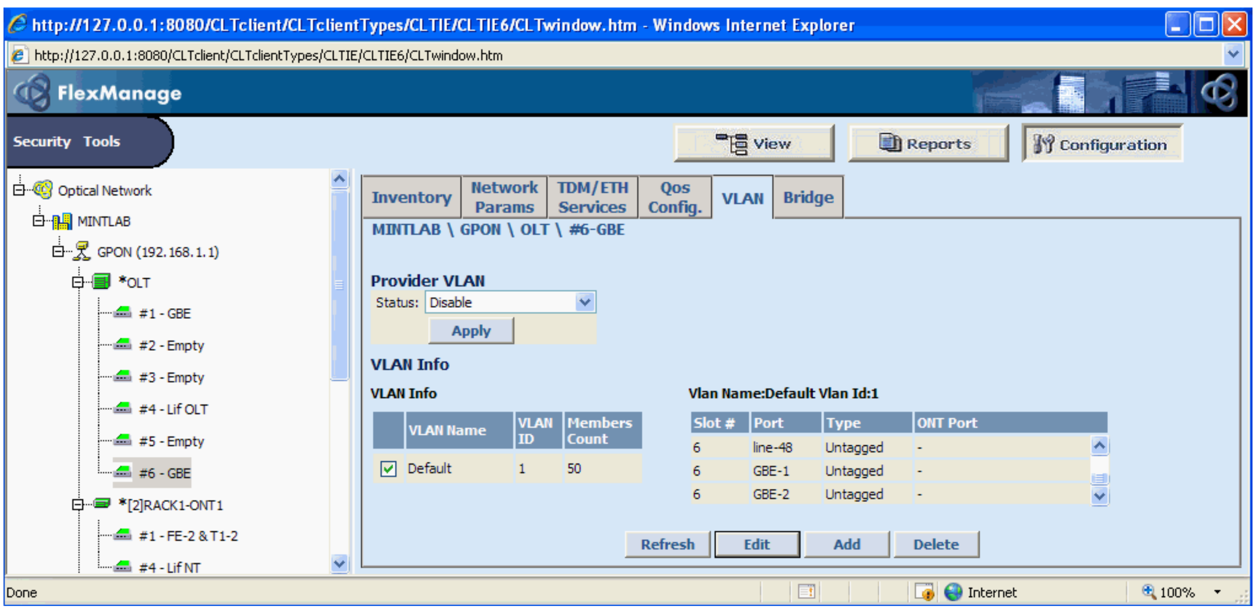
The auxiliary ports can be used for the following purposes:

- In-band management connectivity – used for in-band management access in case the OLT is not located in the CO. In this case the Simple Network Management Packets (SNMP) are received via any of the GbE switch ports, and the packet is forwarded to the auxiliary port that is physically connected to the external management Ethernet port at the LIF card;
- Troubleshoot fast Ethernet ports;
- Act as a local access port at the OLT – used as Metro interface ports.

In order to be usable, the auxiliary ports must be mapped to logical ports. Port 1 is by default mapped to logical port 1 and port 2 to logical port 25. Before routing line port 1 or 25 to the matching auxiliary port, FlexManage ensures that there is no trail set on these ports.

Remarks:

- The GbE port protection feature was not tested. As per FlexLight documentation, in order to enable the protection, the two GbE ports must be connected to the same bridge, or to two different bridges belonging to the same switched cloud;
- By default all the logical ports are members of the default VLAN - VLAN ID 1:

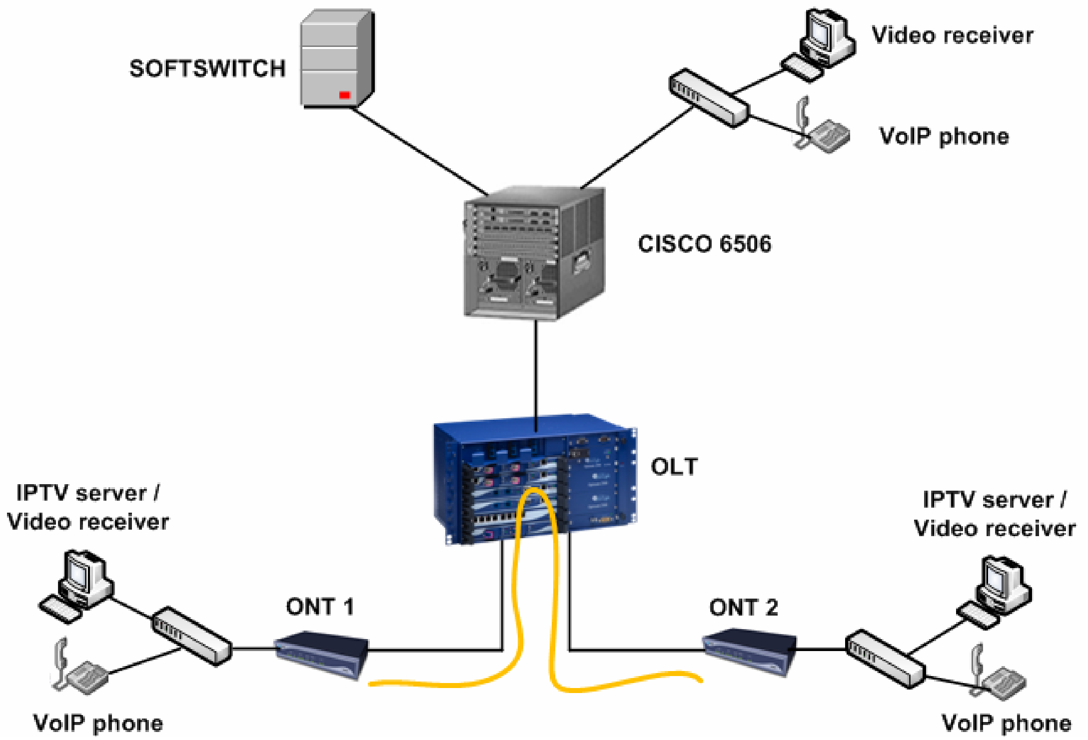


- For dual PON configuration the OLT shelf must be equipped with two GBE cards that will be associated with the LIF cards as follows:
  = Slot 5 or 6 – LIF card in slot 4, first backplane bus, first PON,
  = Slot 1 or 2 – LIF card in slot 3, second backplane bus, second PON.

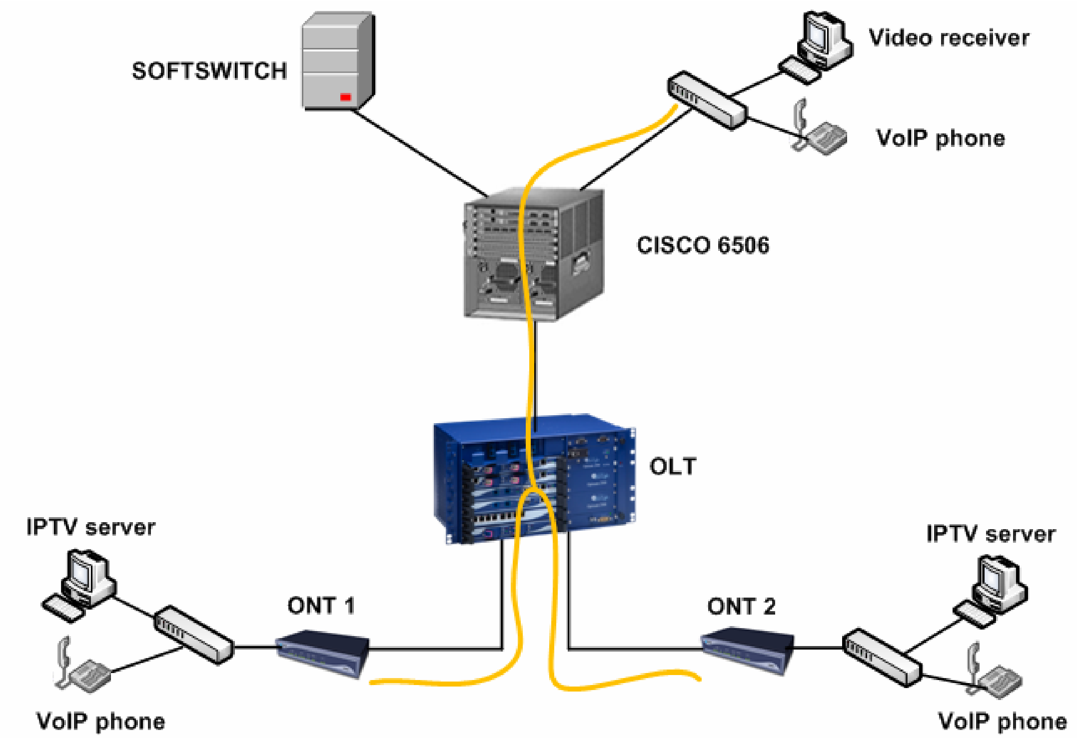
4.3.11. Testing

Tests were performed by sending video files and making VoIP calls for the following scenarios:

1. From / to ONTs in the same PON (single PON):



2. From ONTs to an outside PON receiver:



Remark: all the default parameters were used and no QoS was implemented.

4.3.12. Performance Monitoring

Ethernet Performance Monitoring (PM) function can be used for:

- Monitoring the end-user traffic characteristics using PM counters for Ethernet related events;
- Analyzing the end-user bandwidth utilization;
- Estimation of the physical link quality;
- Qualitative analysis of the end use traffic patterns (unicast and multicast counters);
- Qualitative estimation of the user traffic volume according to actual bandwidth usage

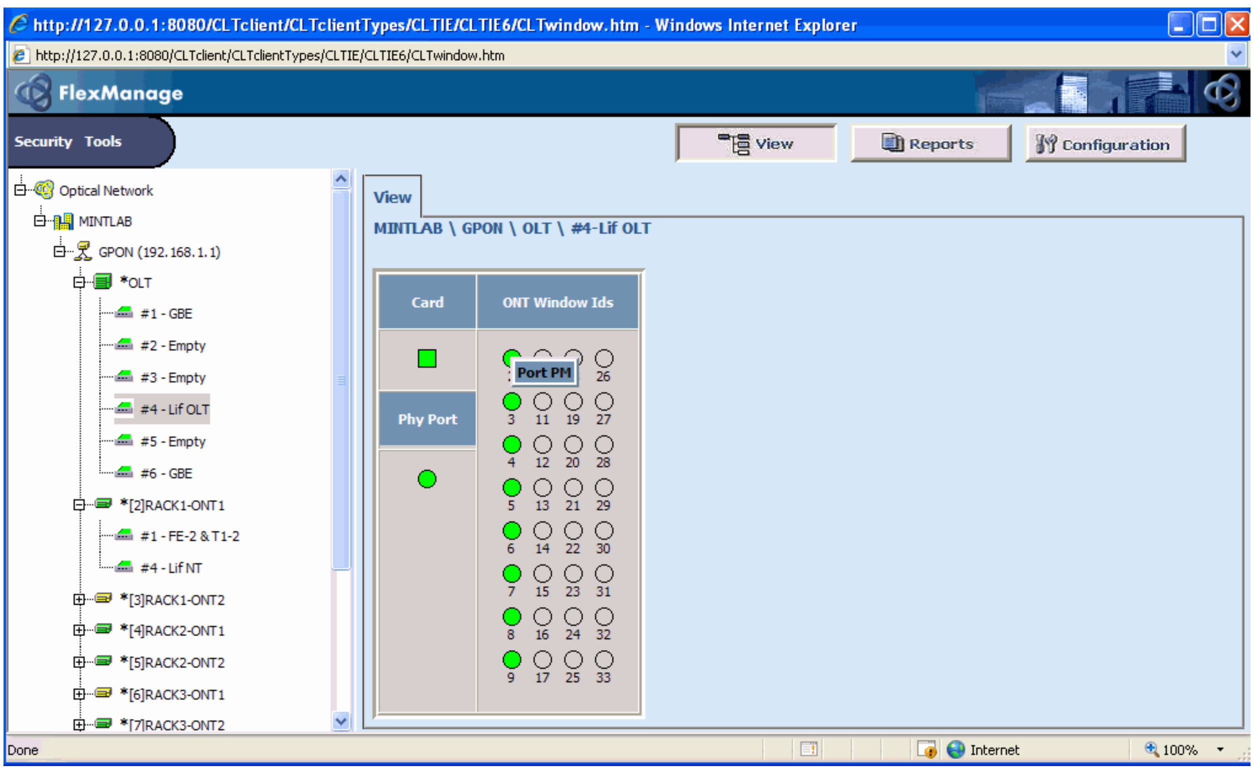
Performance monitoring counters are available for the LIF port and the Ethernet port. Current and historical values are displayed for various counters for 15 minute and 24 hour cycles.

- For the 15 minutes counter (PM15), the historical values are stored for the last 32 PM15 cycles.
- For the 24 hours counter (PM24), the historical value is stored for the previous PM24 cycle.

At the end of the cycle, the current value is saved as historical values, the current counter is reset and a new cycle begins.

In addition to the performance monitoring counters, there are counters for Ethernet ports that are not limited to a time window and are not automatically reset after a 15 minute or 24 hour cycle, but are accumulated over time. These counters are displayed as statistics.

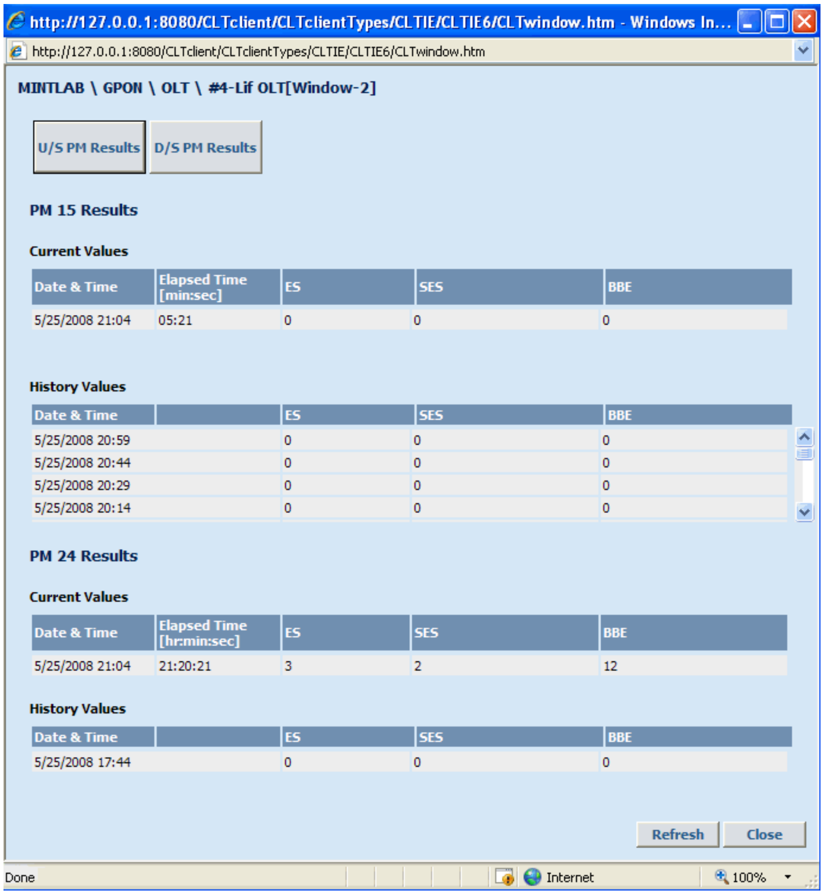
To view LIF performance monitoring results:



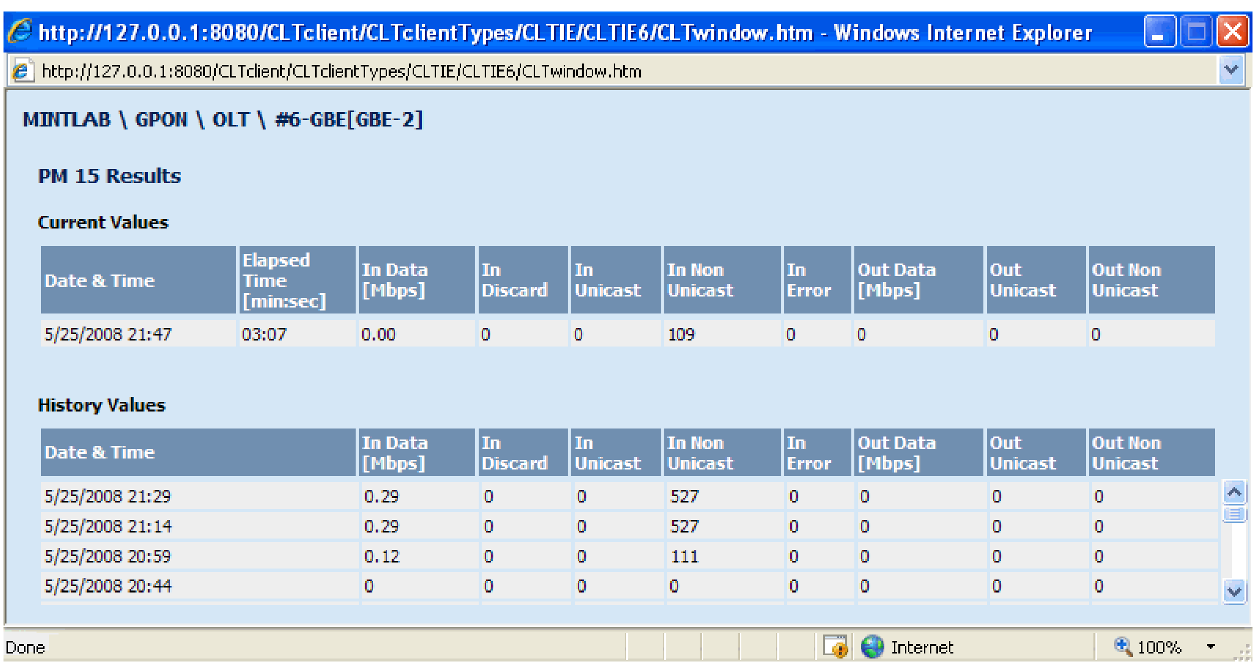
Performance monitoring counters can be displayed for upstream or downstream. In order to view the results for the desired direction click on the corresponding button (see below).

The following fields are displayed:

- Date & Time – the date and time when the values were read;
- Elapsed Time – the time that has passed since the start of the current cycle;
- ES – errors per second;
- SES – severe errors per seconds;
- BBE – background block errors

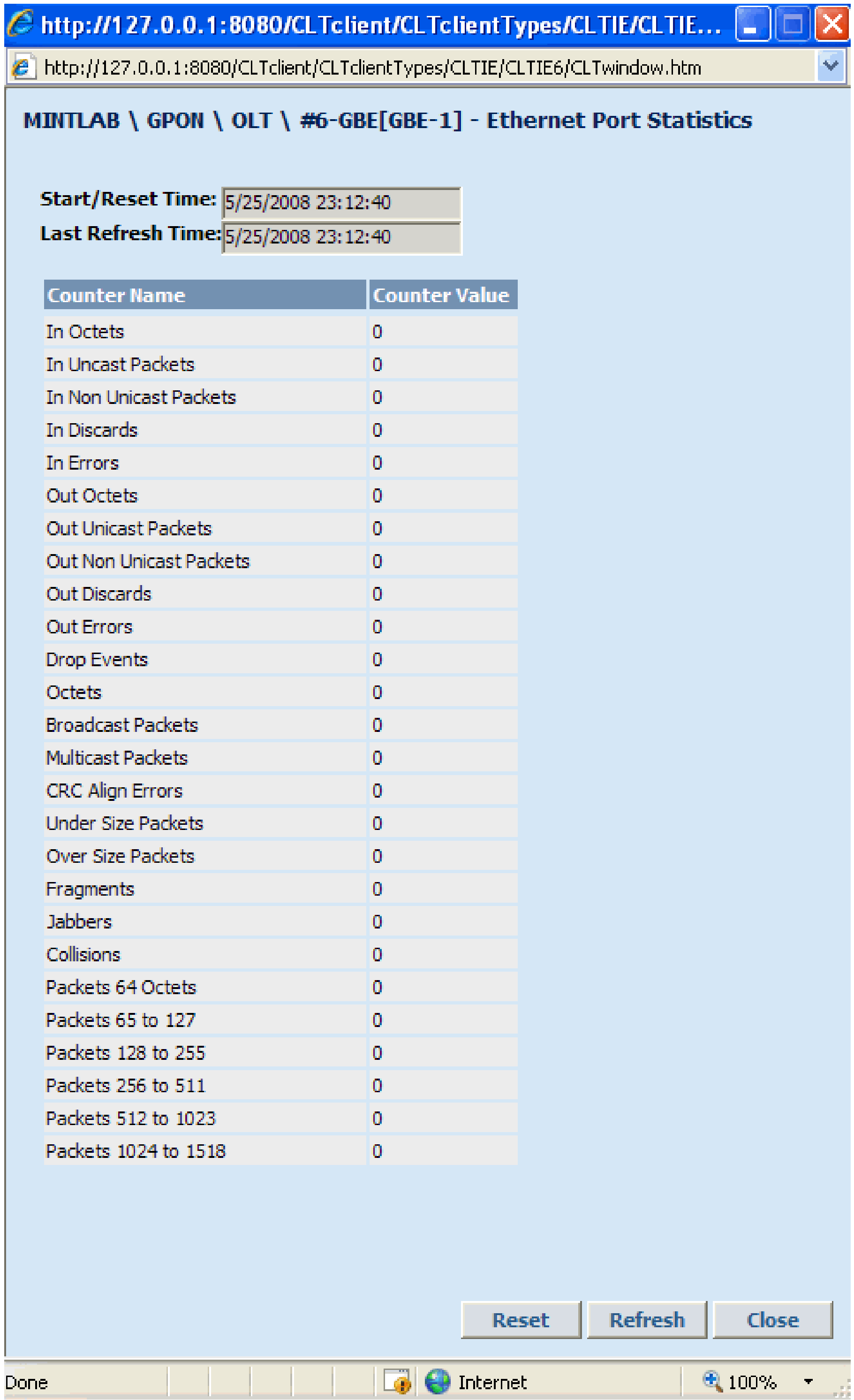


The following results are displayed for the GbE ports and ONTs FE ports:



Not all counters are relevant for all interfaces. If the counter is not relevant, its value in the results table is 0.

To view Ethernet statistics right click on the desired port:



4.3.13. Add VLAN

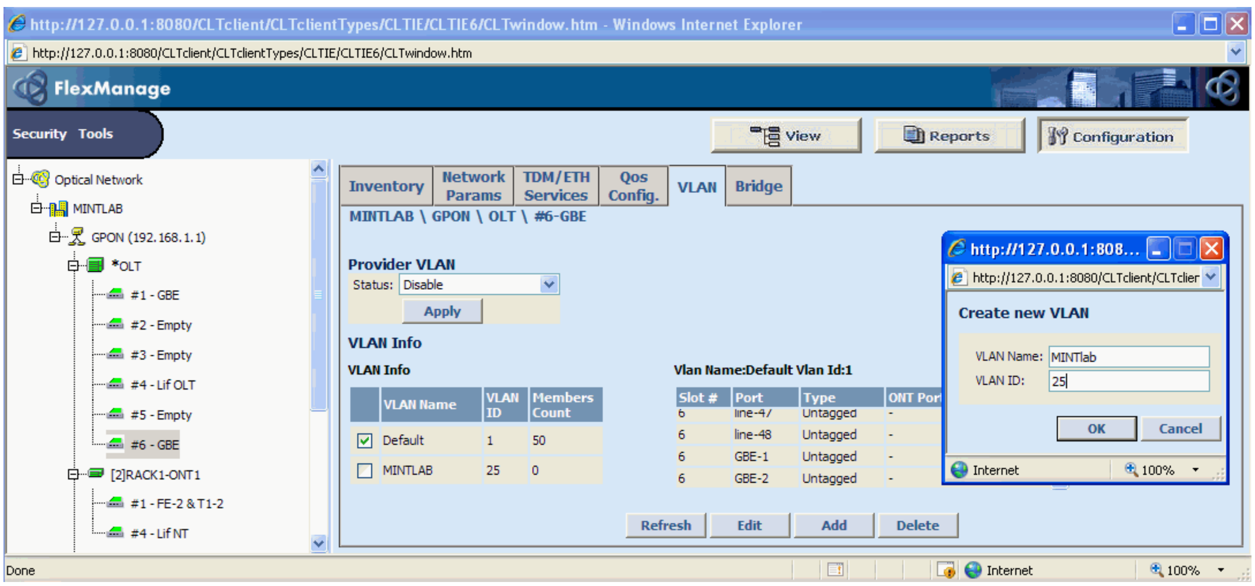
FlexManage is pre-configured with a Default VLAN – VLAN ID 1. Initially, when no other VLANs exist in the system, all GBE and FE ports belong to the Default VLAN. When a new VLAN is created, ports added to this new VLAN are automatically removed from the Default VLAN.

Each port can be a member of several VLANs as a tagged base port, but can only be an untagged port in one VLAN. When a packet arrives at the port, its VLAN tag field is checked. If the VLAN ID matches one of the VLANs of which the port is a member as a tagged base port, then the packet is transmitted to that VLAN. If there is no match (the port is not a member of the VLAN) then the packet is discarded. If the VLAN tag field is empty, it is regarded as if it's intended for the VLAN in which the port is a member as an untagged port

When a VLAN is deleted, the members of the deleted VLAN are automatically transferred to the Default VLAN. The default VLAN cannot be deleted.

To add a VLAN select a GBE card in the Navigation Tree Area in the Configuration mode and click on the VLAN Tab.

A unique name and VLAN ID must be entered in the Create new VLAN window:



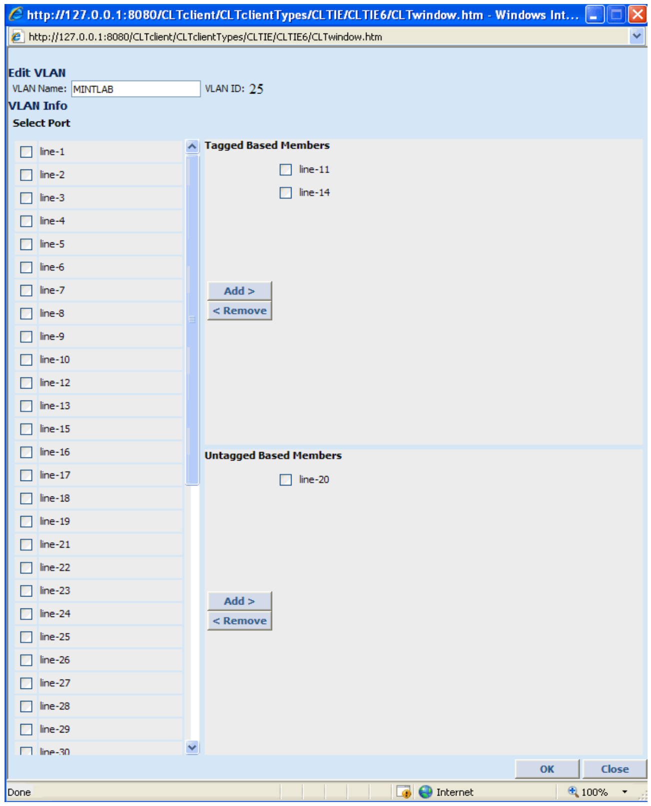
To view the members of a VLAN, select the VLAN from the VLANs list. The VLAN's members are shown in the display area.

The following information is displayed for each VLAN member:

- Slot # - the slot number of the port where the VLAN GBE card resides;
- Port - the type (line or physical) and number of the port;
- Type - the port's VLAN membership type:
  - Tagged – a port can be a tagged based member in several VLANs,
  - Untagged – a port can an Untagged Based member in a single VLAN;
- ONT Port - the destination of the trail. When there is no trail configured in the port, this field will be empty.

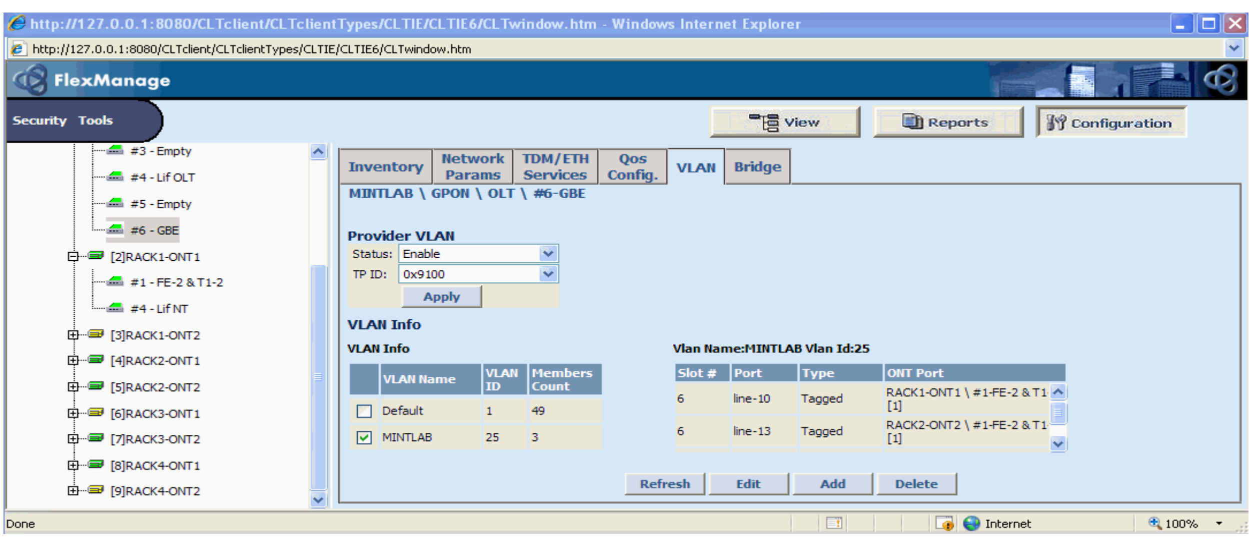
To add / remove members from a VLAN select the desired VLAN and click on the Edit button:

- To add untagged based members - select the ports to be added to the Untagged Based Members list, and click on Add. The ports are added to the Untagged Based Members list and removed from the Select Port List;
- To add tagged based members - select the ports to be added to the Tagged Based Members list, and click on Add. The ports are added to the Tagged Based Members list and removed from the Select Port List;



4.3.14. Provider VLAN

If VLAN configuration (IEEE 802.1Q – Virtual LANs) is used a separation between Ethernet Services can be provided. IEEE 802.1ad – Provider Bridges - is defining a Service VLAN tag added to user packets on the demark point UNI stacked on top of Client 802.1Q VLAN tags, to ensure separation between Provider provisioned Ethernet services and the client internal 802.1Q VLAN tagging. This is known as VLAN Stacking or as Cisco Q-in-Q.



The use of VLAN Stacking allows seamless interconnection between subscriber locations over a wide geographical area. On the ingress UNI point (ONT Ethernet port), the frame is encapsulated with the Provider VLAN tag (P-Tag) and in the egress UNI point the P-Tag is stripped off. This happens whether the client frames have standard 802.1Q VLAN tags (C-Tags) or not. The Provider Tag TPID (Tag Protocol Identifier) may either be the standard 802.1Q 0x8100 value or any of the other proposed standard values (i.e. Extreme Network's 0x9100 or the 802.1ad 0x8101 value). Each end-user packet entering the Provider network must be P-Tagged (encapsulated in a Provider VLAN tag). Each packet leaving the provider network towards the end-user site is stripped of its P-VLAN tag. The transport of the frames is transparent to the subscribers. Layer-2 control protocols frames are treated as regular packets and must be encapsulated with P-Tag, though by default they would never be tagged with a standard Q-tag. In addition, their destination MAC address must be replaced when passing via the provider network in order to avoid being blocked by the provider network bridges.

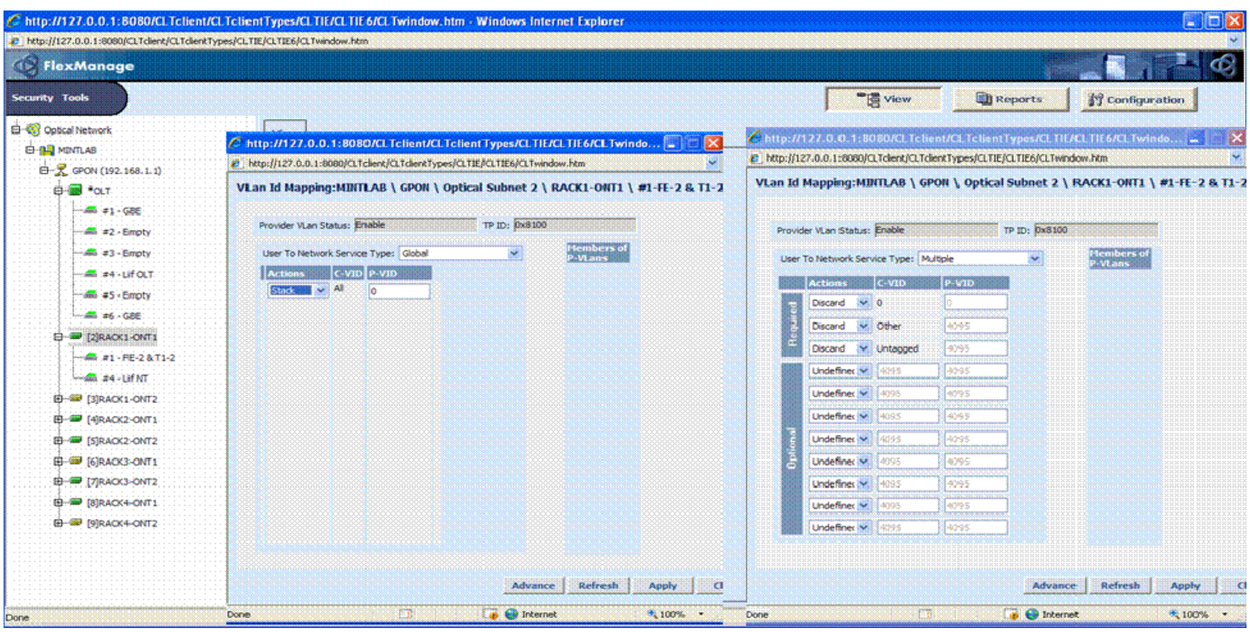
When the Provider VLAN status is enabled, the Provider VLAN tag field is added to the packets set. This field contains the TPID of the provider VLAN and the VLAN ID in the provider's network. Because of this all the OLT FE ports must be configured as untagged.

The VLAN mapping function allows the mapping of each port's C-VLAN ID to a P-VLAN ID. In addition, the priority tags can be mapped from C-VLAN to P-VLAN, and P-VLAN to C-VLAN.

Since the Customer premises are terminated at the ONT (where the Provider premises begin) the VLAN mapping is applied at the ONT FE card and not at the OLT GBE card.

To view and configure VLAN mapping select the desired ONT shelf in the View mode, right click on the FE port and select the UNI configuration. The VLAN ID Mapping window is displayed. The window is based on two service types:

- Global - all of the port's Customer VLAN Ids (C-VIDs) are mapped to the same Provider VLAN ID;
- Multiple - each of the port's Customer VLAN IDs can be mapped to a different Provider VLAN ID. For the multiple options the user has to define specific mapping actions to the following C-VIDs:
  - 0: C-VID = 0,
  - Other: all C-VIDs where no action is defined,
  - Untagged: packet with no C-VID tag;
- Action - select the type of mapping:
  - Replace - replaces the C-VID with the selected P-VID ,
  - Stack – encapsulates the C-VID inside the P-VID field,
  - Forward – packets are forwarded without any changes,
  - Discard – packets are discarded;
- C-VID – Customer VLAN ID. If is not defined, the value 4095 is displayed;
- P-VID – Provided VLAN ID. If is not defined, the value 4095 is displayed;
- Member of PVLANs - A list of all P-VLANs in which the port is a member as tagged (VLAN ID followed by VLAN name).

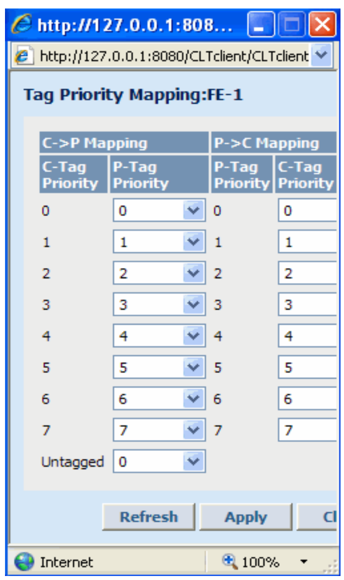


Valid Actions for Multiple User To Network Service Type:

C-VID	Action Type for Multiple				
	Replace	Stack	Forward	Discard	Undefined
	P-VLAN ID is required	P-VLAN ID is required			Used for temporarily ignoring the packet. The default mapping Other will be used instead for this C-VID
0	√	√	√	√	
Other		√	√	√	
Untagged		√	√	√	
Optional (User Defined C-ViDs)	√	√	√	√	√

In addition to mapping customer VLANs IDs to Provider VLAN IDs, the Provider VLAN enables mapping of customer Priority Tags to Provider Priority Tags. Thus, different Priority Tags for the same packet are enabled at both the customer own premises and in the Metro.

In the VLAN ID mapping window, click Advanced. The Advanced Tag Priority Mapping is displayed:



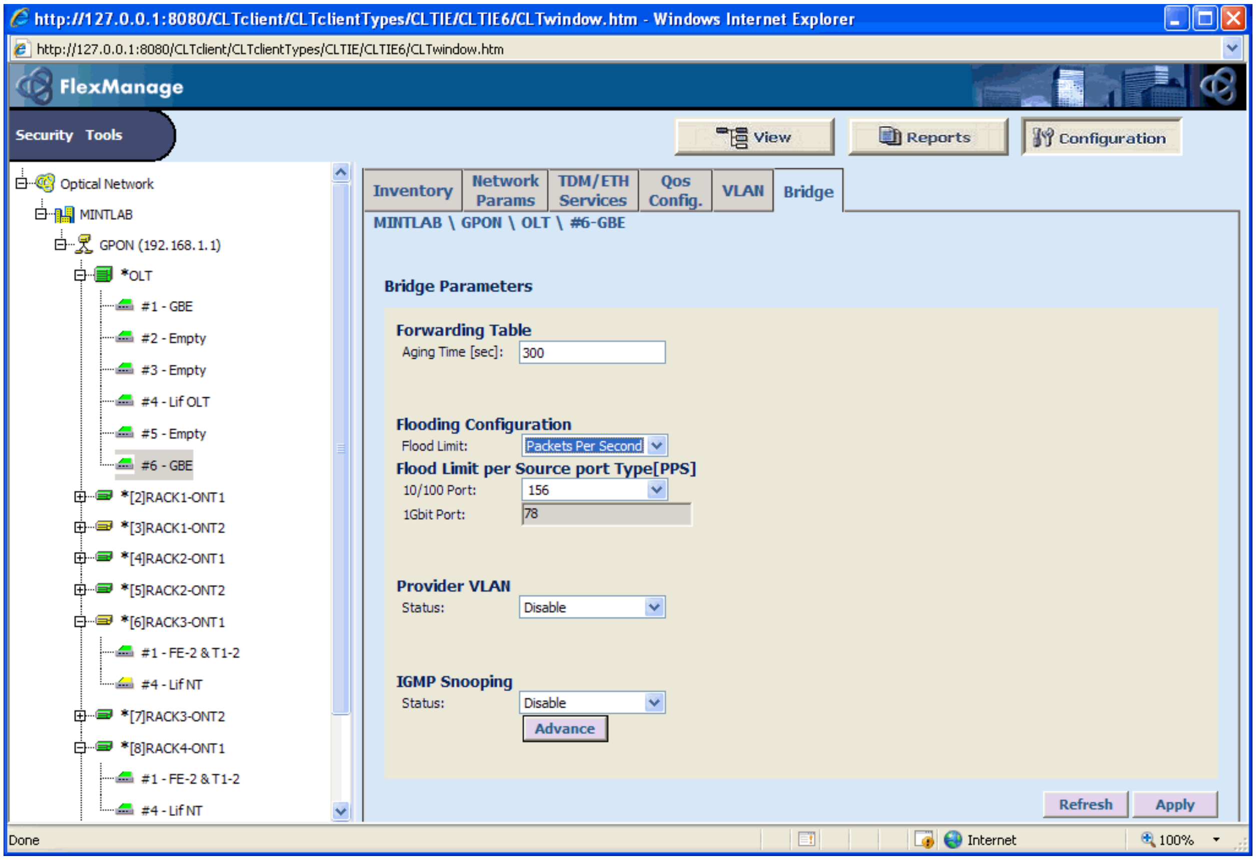
C->P Mapping - Maps the C-VLAN priority to the P-VLAN priority
P->C Mapping - Maps the P-VLAN priority to the C-VLAN priority

4.3.15. Bridge Configuration

The GBE card is composed of a single Bridge, which deals with the Ethernet packets at the MAC layer. To view the Bridge configuration select the GBE card in the Navigation Tree Area in Configuration mode and select the Bridge tab:

A short explanation and possible values for Bridge parameters are given bellow:

- Forwarding Table – the Bridge keeps track of the age of all MAC addresses learned. The MAC addresses that were not been refreshed (re-learned) for more then the Bridge aging time are automatically deleted. Each incoming packet refreshes the Source MAC address once that MAC is already known on the relevant port. The Bridge aging time is measured in seconds and the allowed value range is 10 to 1,000,000 seconds, while the recommended default is 300 seconds (5 min).



- Flooding Configuration – packets which destination MAC address is unknown to the Bridge will be forwarded to all the ports on the same VLAN except the source port. This behavior is meant to ensure that the packet will eventually make its way to the destination host, whose MAC address is the same as the packet destination MAC address. Flooding is by definition a rare operation as most hosts and routers connected to LANs transmit at least one packet after rebooting (be it BootP, DHCP, ARP, DNS or other protocols). Flooding rate is therefore expected to stay very low. High Flooding rates are associated with abnormal network behavior and are related to Denial of Service attack attempts. To help cope with Denial of Service attacks of this kind the GBE Bridge enables the client rate limit the Flooding to one of preconfigured relatively very low rate. The possible values Flood Limit are:
  - Unlimited,
  - Packets Per Second
- Flood Limit per Source Port – displayed only when Packets Per Second value is selected for the Flood limit field:
  - 10/100 Port: 156, 313, 469, 625, 781, 938, 1094, 1250, 1406, 1563, 1719, 1875, 2031, 2188, 2344,
  - 1 Gbit Port - the implemented value is 78;
- Provider VLAN – see 4.3.14. Possible values:
  - Disable,
  - Enable;
- IGMP Snooping – see 4.3.10. Possible values:
  - Disable,
  - Enable.

4.4. GPON Quality of Service

Quality of Service (QoS) refers to the ability of a network to maintain, under congestion, the data flow characteristics of preferred traffic over non-preferred traffic. The goals of QoS include dedicated bandwidth, management of delay variation and latency (required by real-time and interactive traffic), packet loss control, traffic priorities settings, avoidance of congestion, and management of congestion when it occurs.

The packet based QoS assumes that a consistent per-hop behavior (PHB) is maintained in all network nodes that can become a point of congestion. This means that QoS can only be assured if all the nodes that the packet traverses apply the same PHB on packets of the same class. For example, if a class 2 packet gets priority in one node but is delayed or dropped in another one, the overall QoS will not be maintained. Keeping a consistent PHB requires enforcing a QoS Service Level Agreements (SLA) between the various providers and between providers and end-clients.

4.4.1. Classes of Traffic

A packet must be colored with one of the traffic classes defined in the network domain. Coloring is obtained according to the classification decision by setting a value for one of these fields:

- Differentiated Service Code Point (DSCP) field in the IP header;
- Type of Service (TOS) field in the IP header;
- Class of Service (CoS) field in the Layer 2 header.

The CoS and IP Precedence field have 8 classes of traffic (from 0 – the lowest priority to 7 – the highest priority), while the DSCP defines 64 classes.

4.4.2. Congestion Avoidance

Congestion avoidance is achieved through packet dropping. One of the most commonly used mechanisms is Weighted Random Early Detection (WRED). WRED makes early detection of congestion possible and makes use of IP Precedence to determine which packets to be dropped. As a result the packets with higher priority are less likely to be dropped. WRED is not waiting until the queue is full, congestion is detected earlier when the queue fill level is high enough and a managed early packet drop is initiated. Using WRED does not preclude the chance of dropping voice packets (IP precedence of 5) and does not like non-adaptive flows such as UDP because UDP does not have, unlike TCP, its own build mechanism to throttle back.

4.4.3. Congestion Management

Congestion occurs when packets are arriving faster than they can be transmitted. By using congestion management feature, the packets accumulating at an interface are queued based on the packet classification and then scheduled for transmission. Weighted Fair Queuing (WFQ) allocates bandwidth according to IP precedence using weights. WFQ is ideal for the situations in which is desirable to provide consistent response traffic to heavy and light users alike, without adding excessive traffic.

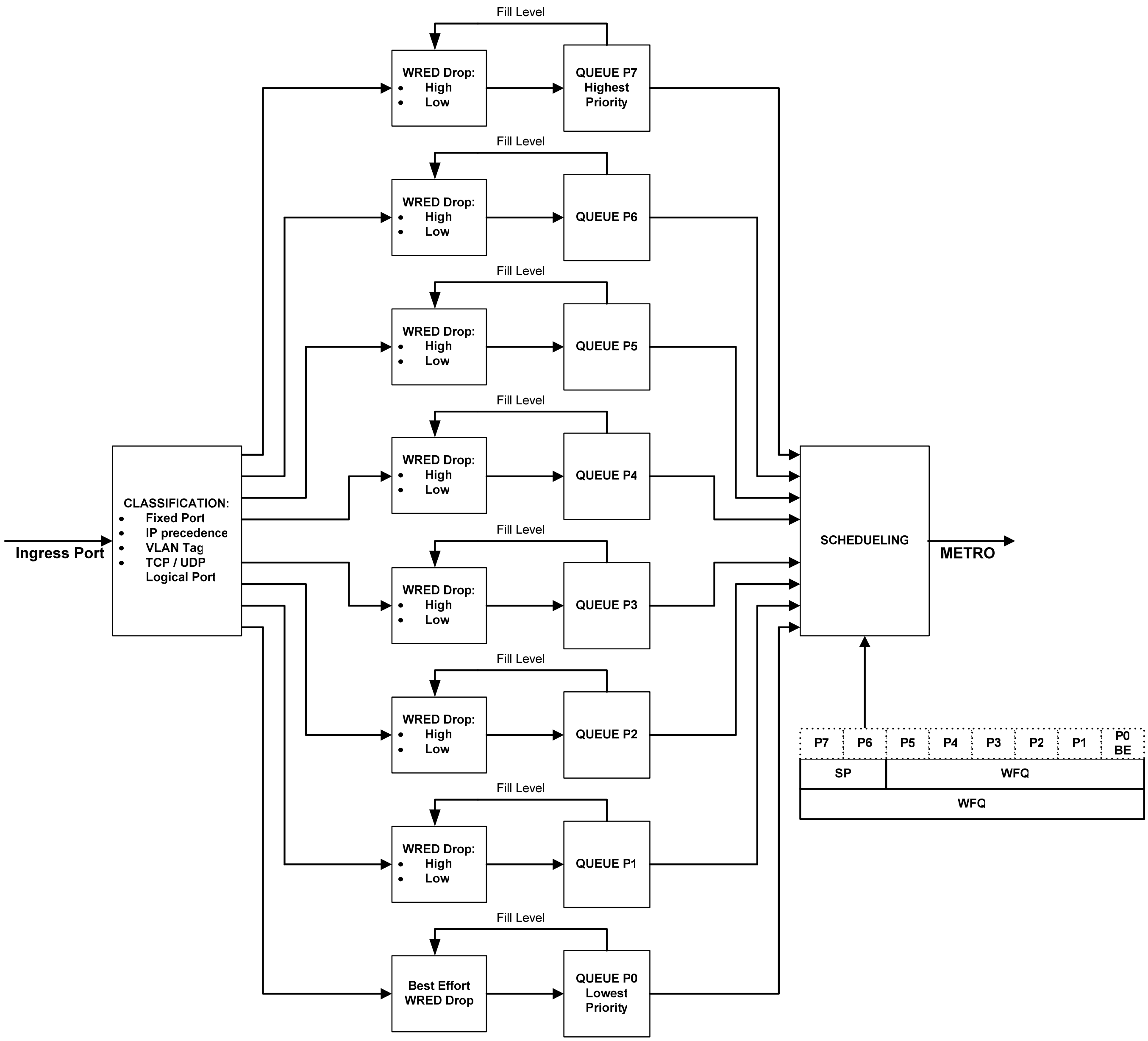
WFQ tries to interleave smaller packets between the larger packets. The decision as to which packet in the queue is allowed to go first is based on the first packet to finish entering the queue. This favors the shorter packets and as a result low bandwidth traffic takes priority over high bandwidth traffic.

Once the priority queues have been serviced the other IP traffic is weighted and queued accordingly. The weighting factor is dependent on the IP precedence. To give an example, if there are three flows with the IP Precedence of 1, 3 and 5, add up (1+1), (3+1), and (5+1) and then divide each by the sum of them: (1+1)/(1+1)+(3+1)+(5+1), (3+1)/(1+1)+(3+1)+(5+1), and (5+1)/(1+1)+(3+1)+(5+1). The first flow will get 2/12 bandwidth, second flow 4/12, and the third flow 6/12 which equals half the bandwidth. A disadvantage of the WFQ is that as the number of flows increases the higher priority flows have a less significant impact because all the flows get served.

Under Differentiated Services standard schemes there might be as many queues as the number of classes serviced by a node. One queue is allocated for Expedited Forwarding (EF) PHB service, while the other queues serve Assured Forwarding PHB and Best Effort services. For EF service a Strict Priority is applied on the EF queue. For enabling Assured Forwarding PHB service, WFQ is employed. Best Effort traffic is serviced only when all the other queues are empty.

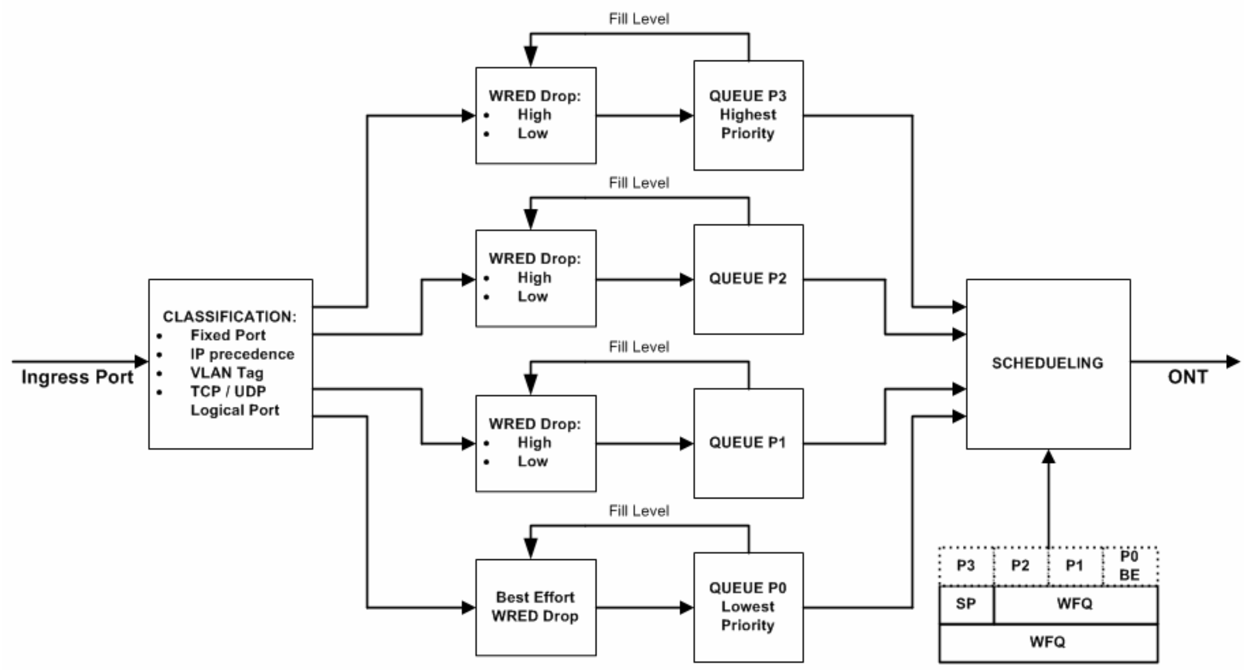
4.4.4. FlexLight QoS.

Every packet entering the OLT is classified and gets one of eight transmit priority values (0 through 7) and one of two drop-priority values (Low or High). After the classification process the destination port or ports is determined. The transmission priority value is used to determine in which queue the packet will wait for transmission, while the drop priority is used to determine whether the packet should be dropped under a certain congestion level on that queue. The congestion level under which the packet is dropped is configurable.

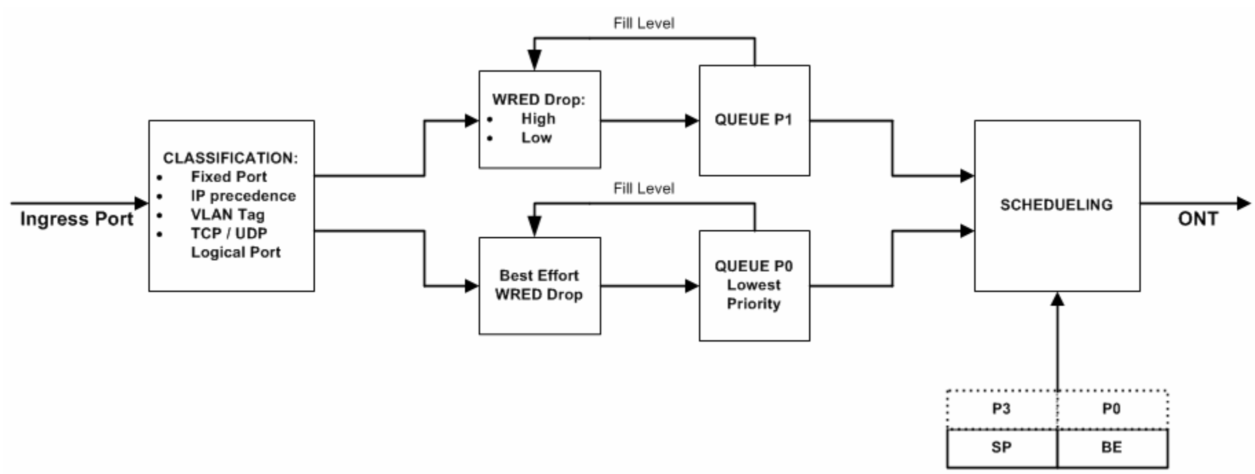


QoS Flow GbE ports Upstream

Each GBE card logical port has four transmit queues defined from the highest to the lowest priority as P3, P2, P1, and P0. Each GbE port has eight transmission queues defined from the highest to the lowest priority as P7, P6, P5, P4, P3, P2, P1, and P0. The ONT ports have two queues P1 and P0 which are serviced as Strict Priority and Best Effort queues. Heavy traffic congestion situations will be controlled by using WRED to throttle down transmission rates.



QoS Flow OLT Logical Ports



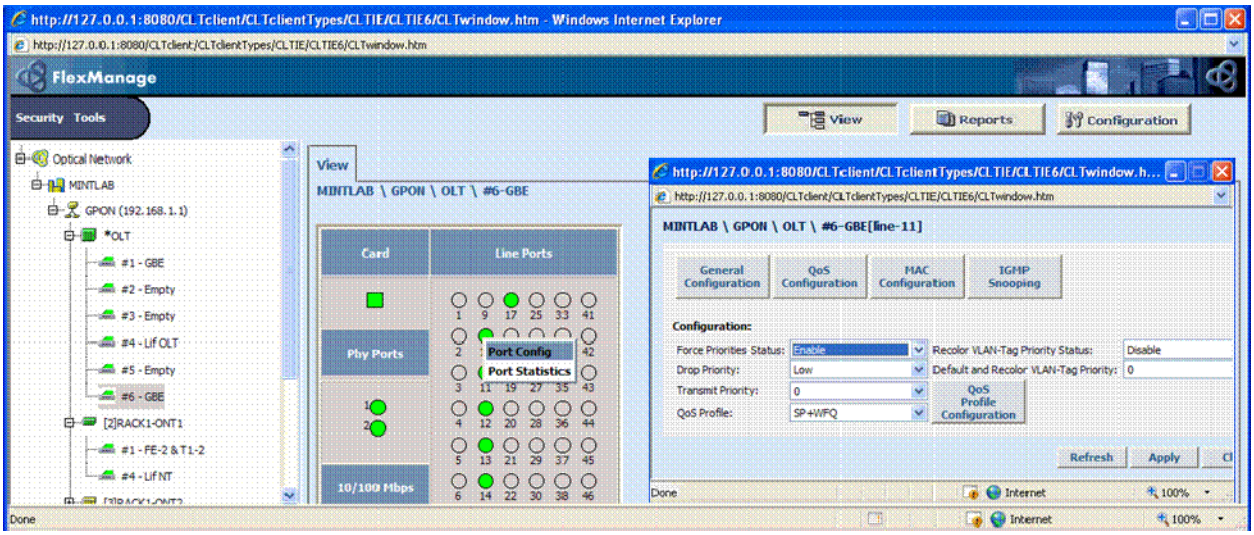
QoS Flow ONT Ports

The following packet information can be used to determine transmission and dropping priorities:

- VLAN Tag priority in the VLAN tag header;
- IP Precedence field value in the IP header - for Expedited Forwarding PHB all six DSCP bits of the Differentiated Services TOS byte definition are used;
- TCP or UDP destination and source logical ports.

The received packets are classified either by the IP Precedence value in the IP header or by the priority field (PRI) value in the VLAN tag. Which of the two is searched first is a switch policy determined globally. If the IP Precedence is preferred but the incoming packet is not an IP packet, then a VLAN tag search is performed and vice versa. If the packet is not IP or VLAN tagged, then transmit and drop priority values are determined according to the source port default transmit and drop priority. Default drop and transmit priority value pairs are defined for each incoming port.

Fixed pre-defined transmit and drop priority pair values are configured per FE or GbE port. Fixed Priority can be forced on a per-port basis, in which case all received packets on that port will be automatically classified to the same pre-configured transmission and drop priority levels regardless of the global policy. This feature is configurable on the OLT ports and on the ONT Physical ports when the QoS status is enabled.

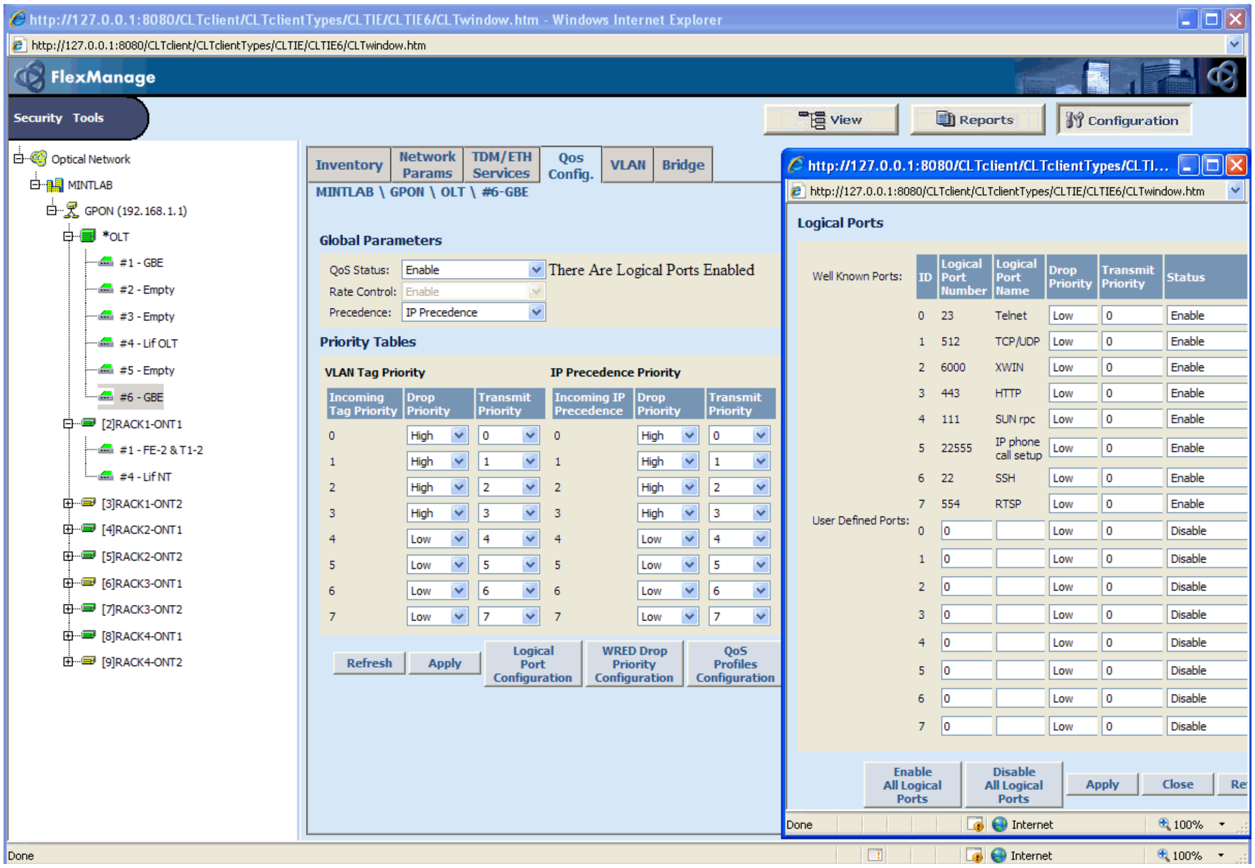


When the incoming packet is VLAN tagged the PRI value is used (802.1p Class of Service priority bits). The 3-bit 802.1p priority field of each incoming packet is mapped to a pair of transmit and drop priority values used within the OLT. According to a global PRI mapping table managed by the user via FlexManage, each packet is mapped into a transmission priority, drop priority pre-configured pair; there are eight transmission priority values (0 to 7) and two drop priority values (High Drop and Low Drop).

When the global classification policy is set for IP Precedence then the classification process checks if the packet is an IP packet. After that the following process takes place:

- The incoming IP Precedence field is analyzed;
- The IP Precedence field is mapped into a value pair transmit and drop priorities:
  - One of the 8 possible transmission priorities,
  - One of the 2 possible drop priorities;
- According to the transmission priority a transmission queue is selected on the egress port. If there is room in that queue for the packet, a pointer to the packet is inserted to the proper queue:
  - In the GbE port, the transmission priority is mapped directly to one of the 8 queues,
  - In the FE port, the transmission priority is mapped into the relevant queue according to the following rule: Priority P to Queue {integer [P/2]},
  - In the ONT the incoming packets are classified into only one of four Transmit priority values 0 through 3 where 3 and 2 are mapped to the P1 the Strict Priority Queue while transmission priority values 0 and 1 are mapped to the P0 (the Best Effort queue)

The Differential Services definition is backward compatible with the IPP values. The exception is EH PHB which assures that packets are transmitted from ingress to egress ports with very low latency. For EF PHB the user must map IP Precedence value 5 to transmit priority 6 or 7 and Low Drop priority. However, in order to ensure EF PHB, the Strict Priority scheduling technique on the egress ports must be selected.



Unless fixed port priority is forced on the ingress port, incoming packets are classified according to the global classification policy. Another exception to the global policy is the case where the incoming packets are IP packets with TCP or UDP header; in this case the source and destination logical ports of the UDP and TCP are checked.

In a logical port based set up, a logical port sometimes provides the application information of the packet. Certain applications are more sensitive to delays than others; using logical ports to classify packets can help speed up delay sensitive applications, such as VoIP.

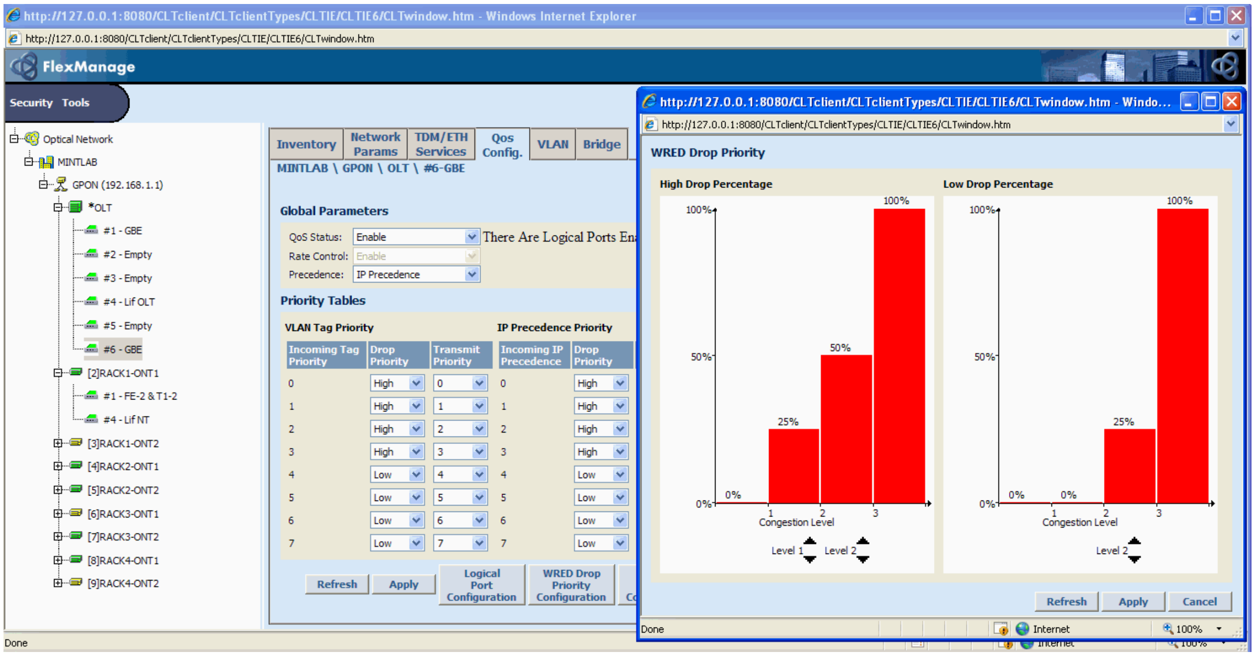
When the incoming frame has an IP packet with TCP or UDP protocols in the transport layer, the 16-bits destination port field and the 16 bits source port field in the TCP/UDP header can be used to define the internal transmit priority and drop priority for the packet. This means that if the source's logical port or the destination's logical port in the packet match any of the programmed logical ports, the packet will receive a transmit and drop priority programmed for the logical port. This feature relates to Destination Logical Port as well as Source Logical Port; both logical port numbers are checked against the logical ports table and the first match counts.

Additionally, up to 8 logical ports ranges can be defined. This provides the flexibility to declare logical ports to specific QoS applications. Any IP packet with a logical port within the pre-configured port range will use the transmission and drop priority specified by the user through the FlexManage.

After the packet transmit priority is used to determine the destination transmit queue on the egress port, the drop priority is applied to determine if the packet is to be dropped. An exception is when the packet is sent to the Best Effort queue in which case the drop priority is not used for congestion control.

When congestion occurs, frame drop is initiated, and the first to be discarded are the packets with high drop priority. If this is insufficient to resolve the congestion, eventually some low-drop priority frames are dropped as well.

WRED congestion control scheme is used. Instead of waiting until the queue is full, congestion is sensed earlier when the queue fill level reaches a certain threshold. If this happens a managed early packet drop is initiated. The number of packets dropped increases with congestion. The queue fill levels at which packets are dropped are configurable, as is the drop probability on each congestion level.



For Level 1 the low drop percentage must always be 0%.
For Level 3 the high drop and low drop percentage must always be 100%.
See table below for the parameters setting of the WRED algorithm applied a FE port:

CONGESTION LEVEL (kBps)	FE QUEUES			DROP PRIORITY	
	P3	P2	P1	High Drop	Low Drop
N > 120	NP3 > A	NP2 > B	NP1 > C	X %	0
N > 140				Y %	Z %
N > 160				100%	100%

The dropping percentage algorithm works as followed:

- N, the total number of bytes in all of the port's queues (but queue 0) is calculated: N = P3 + P2 + P1 when the WFQ Scheduling Algorithm is selected, which in our case applies to both available scheduling techniques applicable on the egress port.
- As N falls into one of the three ranges, packets are dropped from the relevant queue if the following is true:
  - Number of packets in the queues (NP1, NP2, and NP3) is greater than a programmable threshold A, B, or C,
  - Default value for A, B and C is 10? How can this value be changed using CLI?
- If the above two conditions are met packets will be dropped from the respective queues.

For example if the number of packets on queue P3 is greater then 10:

- If N=<120Kb no packet are dropped;
- If 120Kb<N=<140Kb, no Low Drop packets are dropped while X% of the High Drop packets are dropped;
- If 140Kb<N=<160K, Y% of the High Drop packets and Z% of the Low Drop packets are dropped;
- If N>160Kb all packets are dropped.

Parameters settings of the WRED algorithm applied to a GbE port:

CONGESTION LEVEL (kBps)	FE QUEUES						DROP PRIORITY	
	P7	P6	P5	P4	P3	P2	High Drop	Low Drop
N > 120	NP7 > A	NP6 > A	NP5 > A	NP4 > A	NP3 > B	NP2 > C	X %	0
N > 140							Y %	Z %
N > 160							100%	100%

The Best Effort queue is the lowest priority queue (P0 in OLT and ONT ports). Best Effort congestion control use different mechanism than drop priority. When the OLT shared memory space is exhausted and there are at least two packets (called UCC threshold) in the destination queue then ~94% (called B% threshold) of the Best Effort packets are discarded although there is room for more packets in the egress Best Effort queue.

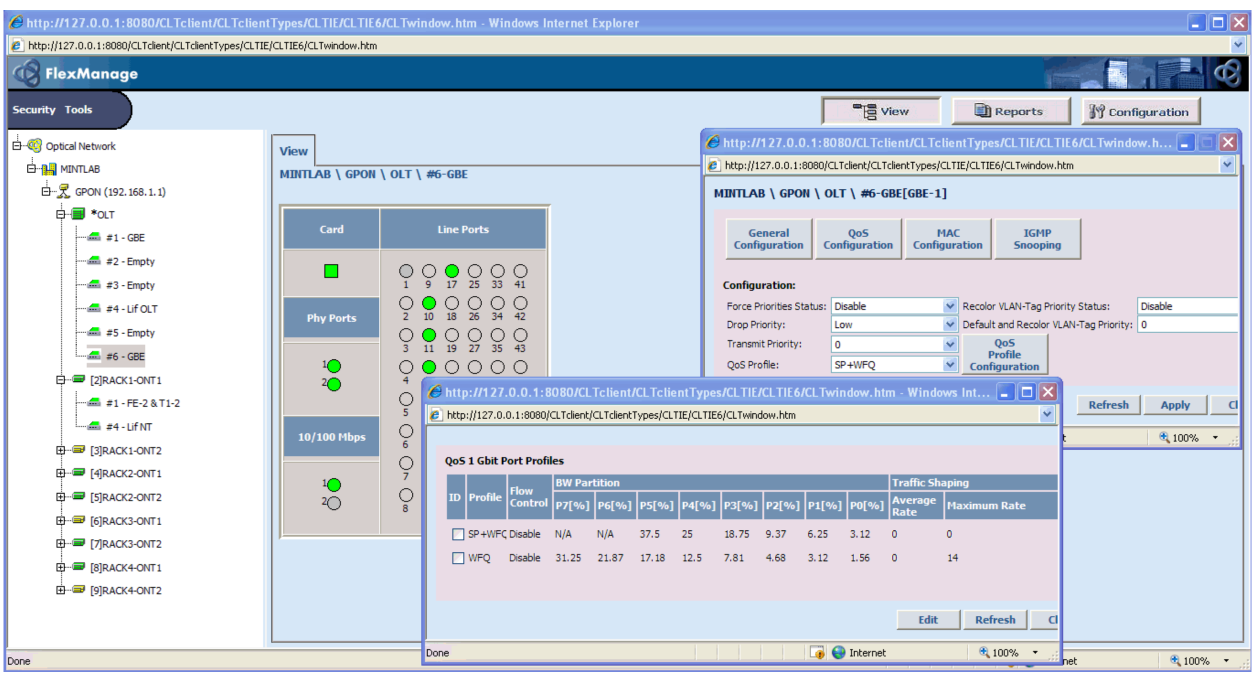
Two scheduling methods are supported per each OLT and ONT port:

- Strict Priority (SP);
- Weighted fair queuing (WFQ),
  - Best Effort (BE).

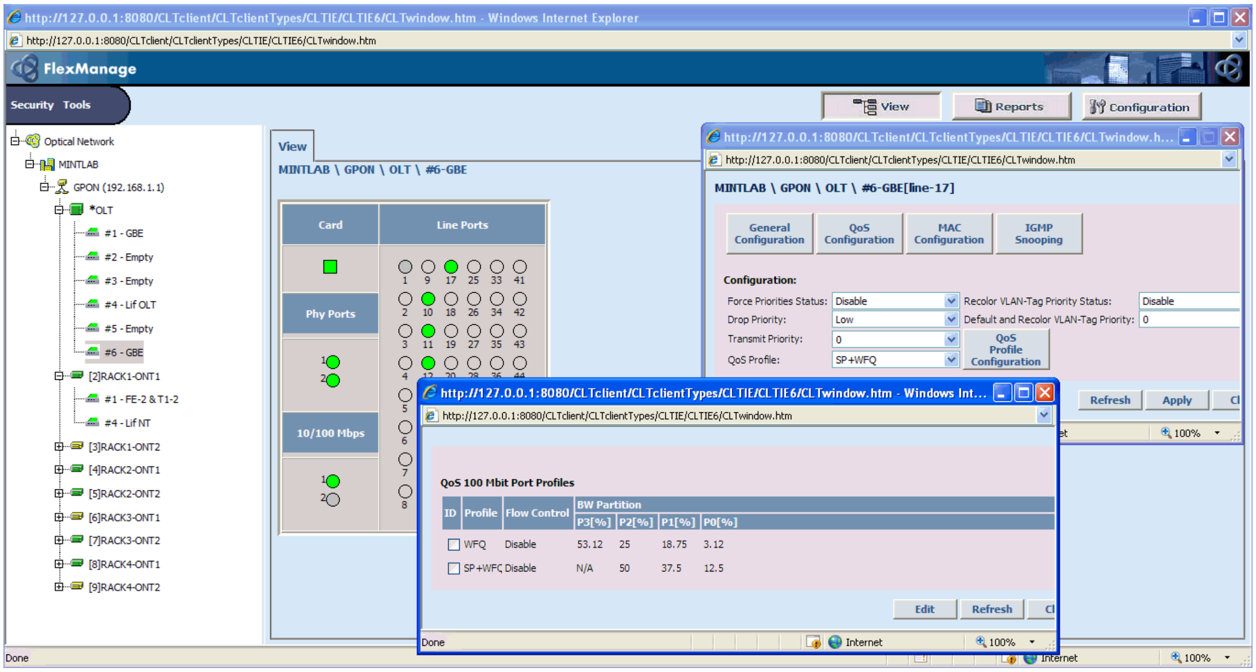
Strict Priority usually applies to the highest priority queue. When strict priority is part of the scheduling algorithm the SP queue is always served as long as there is a packet in the queue; if not other queues are being served. When packet is being transmitted from a non prioritized queue its transmission must be completed even if a packet has just arrived at the SP queue. Only after the lower priority packet transmission is been completed will the packet from the SP queue be served. The SP has to be used for EF PHB.

When Best Effort is part of the scheduling algorithm, a queue only receives bandwidth when none of the other classes have any traffic to offer. None of the two QoS configurations include best effort queues but P0 in all cases can be referred as Best Effort. The Best Effort class should be used for non-essential traffic, since no performance assurance is provided.

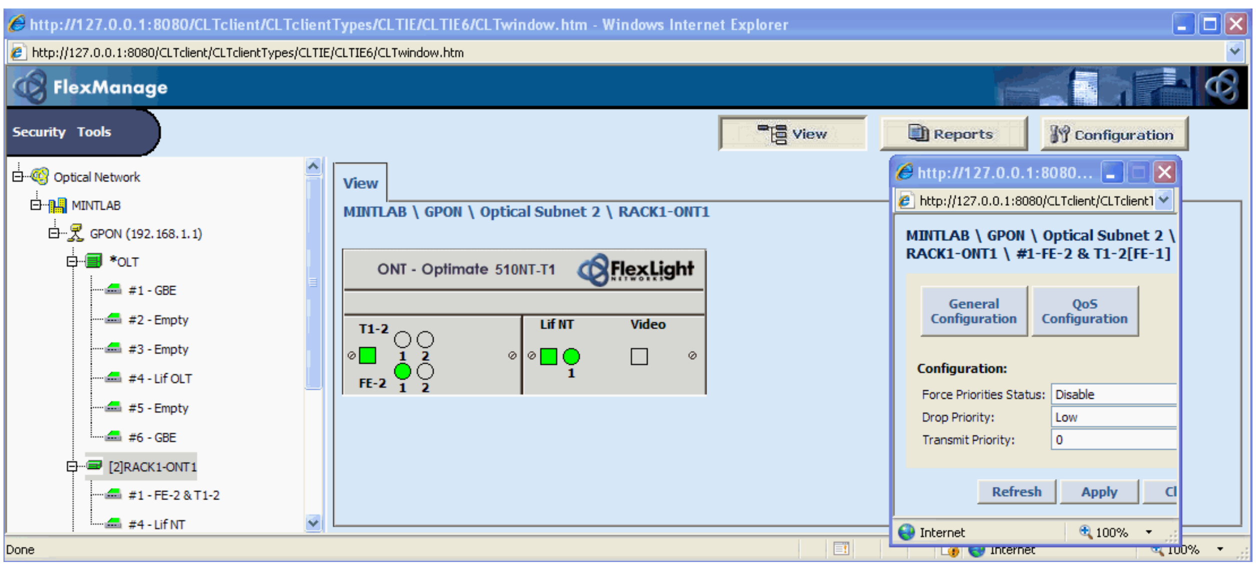
On each GbE port one of the two different scheduling techniques can be mapped:



On each FE port one of two different scheduling techniques can be mapped.



On each ONT line port there are only two queues P0 and P1 while P1 is always strict priority. Note that there is no alternative and therefore no scheduling technique selection on the ONTs.

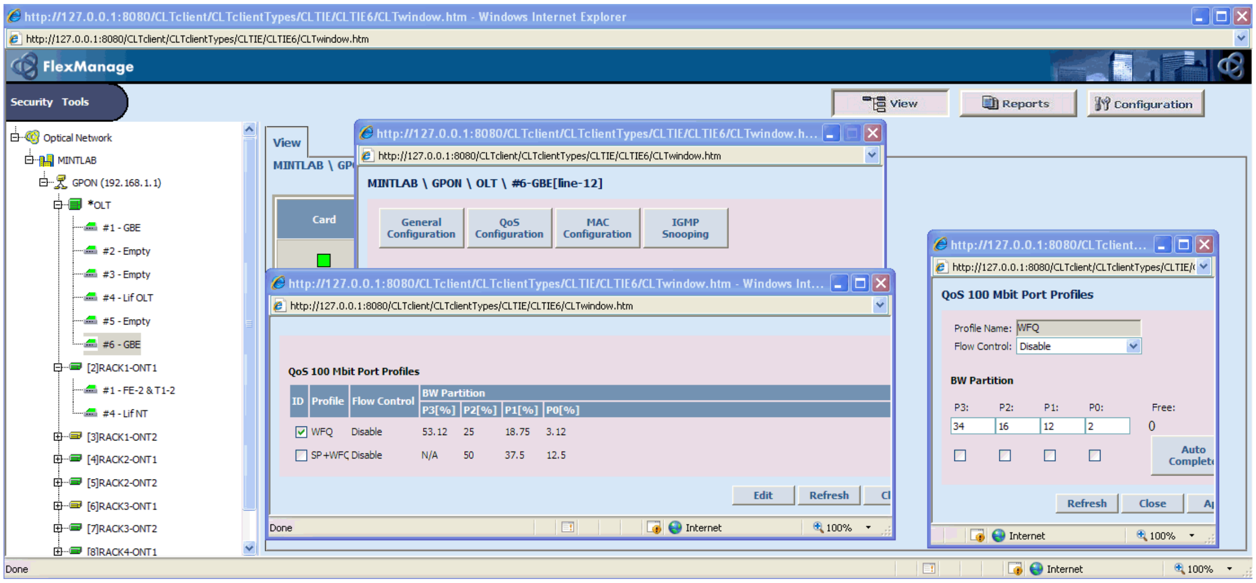


WFQ scheduling assures that the queues will be serviced according to a pre-defined time-share. Four WFQ weights can be set (eight for Gigabit ports) that are associated with the different priority queues. The WFQ algorithm assures that each priority queue will receive the relative drain share out of the total service rate set by the port rate. The fairness comes from the fact that even if a queue is allocated 0 drain weight the scheduler still services single packets.

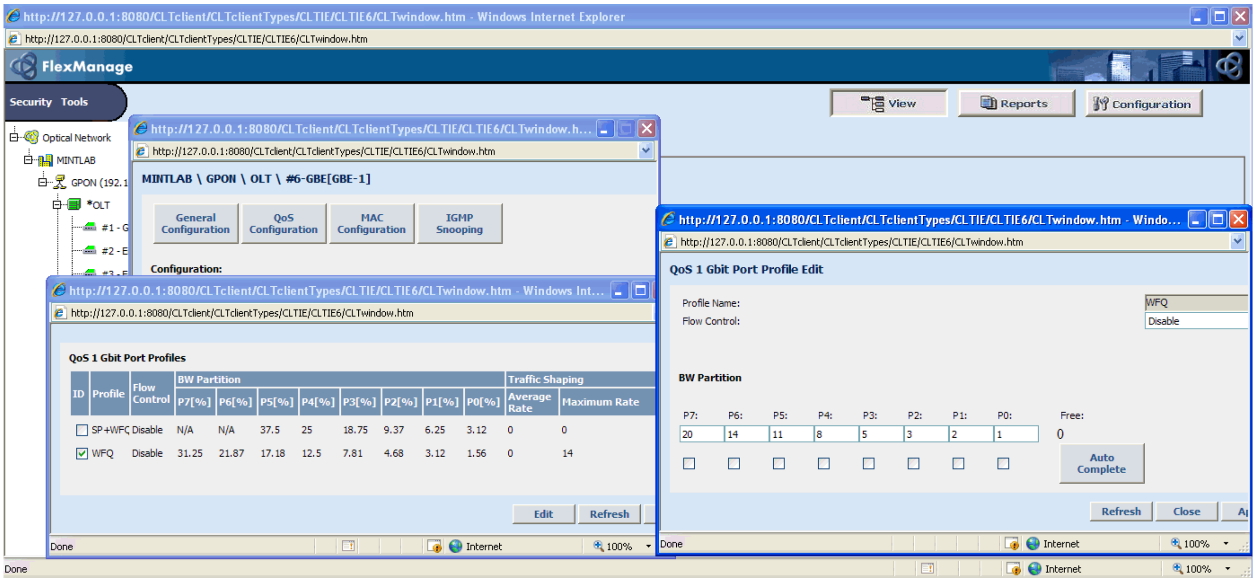
To attribute relative bandwidth share partitioning, weights associated with the desired queue drain size partition are defined for each queue. The weighted fair queue for 10/100 ports are implemented by defining W0, W1, W2 and W3 to be the weights associated with the desired relative drain weights for queues P0, P1, P2 and P3 respectively. The weighted fair queue for 1G ports are implemented by defining W0, W1, W2, W3, W4, W5, W6 and W7 to be the weights associated with the desired queue relative queue drain partition for queues P0, P1, P2, P3, P4, P5, P6 and P7 respectively. Any assignments of the weights have to satisfy the following two requirements:

- All weights are whole numbers;
- The weighted sum must be 64.

BW partition FE ports:



BW partition GbE ports:



An empty queue will let the other queues share the port service rate relative to their total allocated weights. If queues P0, P1, P2 and P3 have the relative drain weights of W0, W1, W2, and W3, and assuming that queues P1 and P3 are empty, then when traffic flows to P0 and P2 the relative service rate will be:

- (Port Rate)×W0/(W0+W2) for P0;
- (Port Rate)×W2/(W0+W2) for P2.

For example, on applying different weights to the priority queues for WFQ scheduling on a 50 Mbps port, the service rates for congested queues can be calculated using the following formula: Weight=64×BW/50.

QUE	P3	P2	P1	P0	TOTAL
WEIGHT	16	32	12	4	64
Actual service rate when all queues are congested	12.5 Mbps	25 Mbps	9.375 Mbps	3.125 Mbps	50 Mbps
Actual service rate when traffic flows only through P3 and P2	16.7 Mbps	33.3 Mbps	0 Mbps	0 Mbps	50 Mbps

To ensure downstream / upstream traffic is limited to the requested client GBR, each FE port service rate is limited to an average GBR rate. The Rate Control parameter ensures that for each line port a possible congestion occurs within the OLT, thereby enabling the QoS policy to take place. This requires complete absorbing of packets transmitted by the switch towards the adaptation Ingress FIFO.

Whenever the user changes the SLA of an Ethernet port, the rate limit value is applied at two points:

- According to the requested guaranteed BW, the port is allocated with the appropriate PON transmission resources;
- The Ethernet OLT port.

Two parameters are used to control the average rate for a FE port:

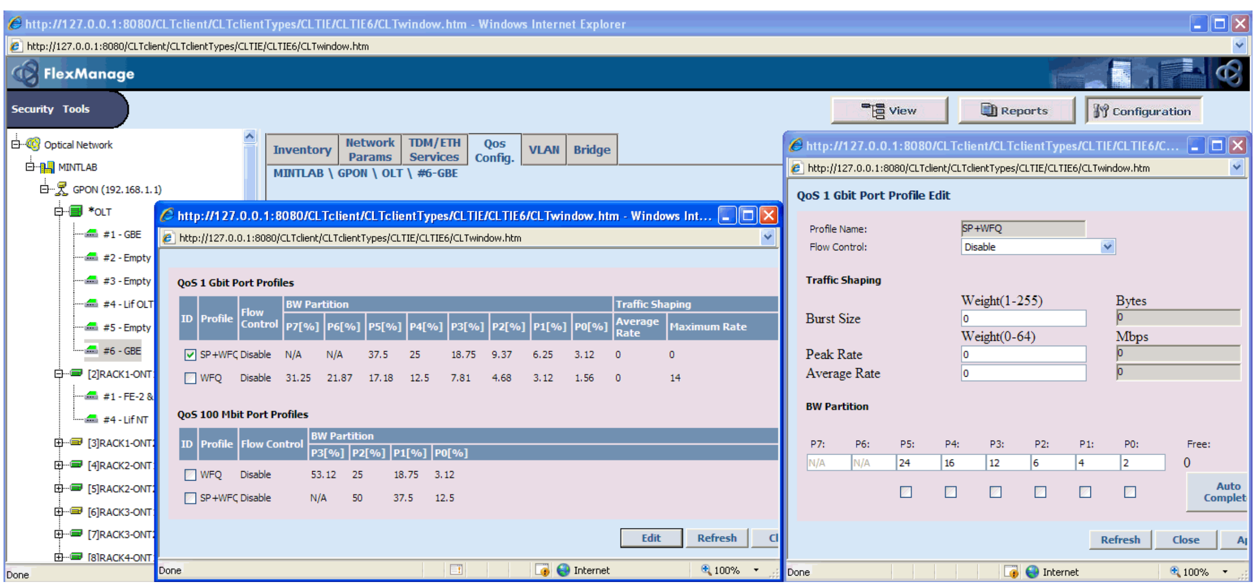
- M – number of bytes to be transmitted;
- N - time.

Only M is programmable, while N is by default 10 ms. The value of M/N will equal the average data rate of the outgoing traffic aggregated on the given FE port. Although there are many (M, N) pairs that may have the same average data rate performance, the smaller the time interval N, the “smoother” the output pattern will appear. As such, the minimal 10 ms value is used.

The rate control within the OLT is statistical and packet size dependent. Since the Rate Control mechanism accounts for transmitted bytes only and compulsory Inter-Packet Gap is omitted from calculation, actual transmitted BW ends up being greater then configured. When only 64 Byte packets are transmitted the actual output BW under congestion is 116% of the configured limited rate.

Rate control setting is enabled automatically when QoS is implemented.

Traffic Shaping is used to control the peak and average rate of traffic exiting the OLT.



Traffic Shaping is more accurate than rate control, as it applies a token bucket algorithm on the queue packets servicing mechanism. Nonetheless, it allows excess traffic rate peaking above the predefined normal rate.

Traffic Shaping applies only to the GbE ports and only when Strict Priority scheduling technique is used. It is used to limit Expedited Forwarding service traffic, which is the reason why it is restricted to queue P6 (the second highest priority queue) and only on the GbE port.

Traffic Shaping has the following configuration parameters:

- Peak Exit Rate - [n/64 %] where $1 \leq n \leq 64$. The percentage should be multiplied by 1000 Mbps. Peak rate is actually W6 - the BW weight share for queue 6;
- Average Exit Rate - [k/64 %] where $1 \leq k \leq 64$. When k = 0 Traffic Shaping is disabled;
- Maximum Burst size – in 16 Bytes granularity with range between 1 and 255 (16 to 4080 bytes)

Peak rate is set using a programmable whole number, no greater than 64. For example, if the setting is 32, then the peak rate for shaped traffic is 1000 Mbps×32/64 = 500 Mbps.

Average rate is also a programmable whole number, no greater than 64, and no greater than the peak rate. For example, if the setting is 16, then the average rate for shaped traffic is 1000 Mbps×16/34 = 250 Mbps. As a consequence of the above settings, shaped traffic will exit the GbE port at a rate always less than 500 Mbps, and averaging no greater than 250 Mbps.

Remark: the implementation of QoS is a tedious process which requires an in depth knowledge not only of the equipment capabilities and configuration parameters, but also of the way in which their implementation may affect the behavior of the network.

Conclusion

Telecommunication companies have various options for deploying the capacity necessary to support bandwidth intensive consumer and enterprise video and data services. Besides ample bandwidth to support long term growth in services and subscribers, GPON has the following benefits:

- Is a proven technology - standards finalized in 2005. The first commercial deployment in North America was in 2006; subsequent deployments have proved GPON ability to support various carrier and enterprise applications.
- Is a fiber based technology. GPON does not have the distance limitation of copper based technologies.
- Supports a mix of voice, video and data services (triple-play services).
- Employs passive network infrastructure; as a result of the low subscriber equipment costs, low maintenance and replacement cost, it has low Opex and Capex.
- Uses encryption algorithms - security is a major asset in enterprise market.
- Supports TDM services in addition to providing transport of packet data.
- Offers Quality of Service to ensure delivery of high-quality voice, data, video, and allows service differentiation.

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