

## Optical Access Network Migration from GPON to XG-PON

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**Abstract**—The purpose of this paper is to give an introduction into the new standard base of next-generation Passive Optical Network (NG-PON). Study and analysis of future trends in the development of next-generation fixed broadband optical network is performed. The main intention of this paper is to describe migration from Gigabit-capable Passive Optical Network (GPON) to Ten-Gigabit-Capable Passive Optical Networks (XG-PON). Paper answers the question of what extent active and passive GPON elements need to be replaced and what needs to be added when migrating to XG-PON. Special focus is also pointed on the coexistence of GPON and XG-PON.

**Keywords**—passive optical network; Gigabit PON; XG-PON; fiber to the home; optical access network

### I. INTRODUCTION

With new services like three-dimensional high-definition television, cloud computing, more and more internet based applications the required bandwidth to the end user is increasing constantly (approx. 50% per year by Nielsen's law [1]). This gives the infrastructure providers an opportunity to offer new services and consequently increases average revenue per user, and thus they need to make smart decision about the investment into Fiber to the x (FTTx) technology, where x stands for node, cabinet, curb, cell, building, premises or even home as an ultimate and final solution.

It is the common fact that running fiber to the end customer (to the home) is the best possible option. After making the decision for FTTH there are two basic architectures possible. One is point-to-point (P2P) [2] and another is point-to-multipoint (P2MP) typically seen on the market as PON (Passive Optical Network) technology.

Most of the recent deployment in Europe and America is based on GPON system standardized by ITU-T series G.984 [3]. It offers downstream speed of 2.4 Gbit/s typically for up to 64 users and upstream speed of 1.2 Gbit/s. Since fiber as a media can transport much more, operators are expecting more from FTTH technology.

Present Gigabit-capable Passive Optical Network (GPON) as a future safe investment new standard for first generation of Ten-Gigabit-Capable Passive Optical Networks (XG-PON1) has been published in 2010 by ITU-T [4]. This standard will offer 10 Gbit/s downstream and 2.5 Gbit/s upstream speed; but, target distance and split ratio did not increase much. Research in this area continues the job to bring even better P2MP technology. Most of them are today known under the term second generation of next-generation Passive Optical Network (NG-PON2). Incorporating the Wavelength-Division Multiplexing (WDM) technology is mandatory to go beyond XG-PON data rates, splits and reach. The main difference between XG-PON1 and NG-PON2 from operator point of view will be the migration strategy. Since the NG-PON2 will use brand new technology, coexistence of GPON and NG-PON2 will be difficult.

This paper presents the migration from GPON to XG-PON. As an enhancement to GPON, XG-PON1 inherits the framing and management from GPON. XG-PON1 provides full-service operations via 4x higher rate and 2x larger split to support a PON network structure. In Section 2 of this paper basic technology and up-to-date standards status are described. Section 3 contains main points in the XG-PONs deployment and development: general description, coexistence with previous standards, physical layer capability, etc. Some information on the RF CATV co-existence inside XG-PON is also described. Section 4 contains information on the examples of products for WDM filters that are planned to use in XG-PON1, possible candidates for OLT filters and also information on the tunable lasers, their possible applications for NG-PONs systems, advantages and disadvantages. Section 5 summarizes the overall conclusions.

### II. BASIC TECHNOLOGY DESCRIPTION

#### A. Gigabit PON

Efforts to standardize PON networks operating at above 1 Gbit/s were initiated in 2001 as the ITU-T G.984 series of recommendations [3]. GPON attempts to preserve as many

characteristics of the G.983 series [5] of recommendations as possible, however, due to technical issues related to providing the higher line rates, the BPON and GPON systems are not interoperable.

At the moment, GPON standards have seven transmission-speed combinations (line rates): symmetric 1.2 or 2.4 Gbit/s; or asymmetric 1.2 or 2.4 Gbit/s downstream with 155 Mbit/s, 622 Mbit/s, or 1.2 Gbit/s in the upstream. But in fact there is the only one useful standard, which is 2.4 Gbit/s downstream and 1.2 Gbit/s or 2.4 Gbit/s upstream.

As with BPON, the network may be either a one or two-fiber system from the Optical Line Terminal (OLT). In the downstream direction, GPON is also a broadcast protocol with all Optical Network Terminals (ONTs) or Optical Network Units (ONUs) receiving all frames and discarding those not intended for them (Figure 1). Upstream transmission is via the Time Division Multiple Access (TDMA) and is controlled by an upstream bandwidth map that is sent as part of the downstream frame.

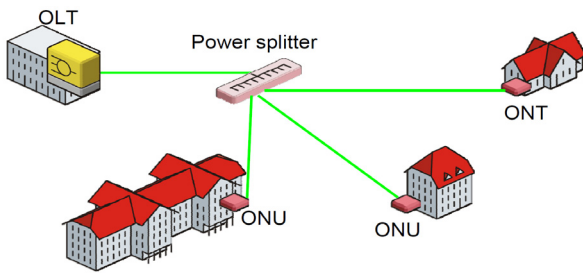


Figure 1. GPON consists of Optical Line Terminal (OLT), Passive Optical Splitter, Optical Network Units (ONU) or Optical Network Terminals (ONTs).

Up-to date GPON OLTs are able to support split ratios of 16, 32, or 64 users per fiber. ITU-T G.984.2 includes future ratios of up to 128 users per fiber and accounts for this in the transmission-convergence layer. According to G.983.3 (Figure 2), for a single-fiber system, the operating wavelength is in the 1480 nm to 1500 nm band in the downstream and in the 1260 nm to 1360 nm band in the upstream. This leaves the 1550 nm to 1560 nm band free for RF overlay video services. For a two-fiber system: in the 1260 nm to 1360 nm band in both the downstream and the upstream directions.

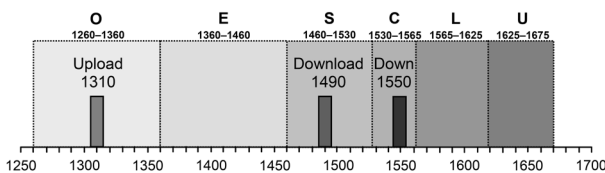


Figure 2. ITU-T definition of telecommunication wavelength bands with three operating windows. 1310 nm is used for upstream. 1490 nm and 1550 nm are used for downstream.

B. XG-PON1

General XG-PON1 physical layer specifications were finalized in October 2009 and published by ITU-T in March 2010. XG-PON1 wavelength plan was a problem discussed in FSAN/ITU-T by vendors and operators. Driven by the optical transceivers market, FSAN/ITU-T selected the narrow downstream wavelength range of 1575 nm to 1580 nm, because it is the only wavelength band that is left in the system crowded with RF overlay video services. This choice has advantage that it also matches the downstream wavelength selection included in 10G-EPON draft standard.

The overall XG-PON and GPON optical spectrum is illustrated in Figure 3. C-, L-, and O- bands were compared in the selection of upstream wavelength. The first option of C band overlapping with the RF overlay video channel was eliminated. The L band was also eliminated due to the insufficient guard band between upstream and downstream wavelengths. After all, the candidate wavelength was narrowed down to O- band and O+ band. Comparing the pros and cons (such as complexity and costs), O- band was selected because O+ band has higher requirements on filters and is more expensive. Wavelength for upstream is 1260 nm to 1280 nm.

The downstream rate of XG-PON1 was defined as 10 Gbit/s, which was mainly driven by the well-established and low-cost 10 Gbit/s continuous transmission technology in the industry. The exact rate is 9.95328 Gbit/s that keeps the consistency with typical ITU-T rates. This is different from the rate of the IEEE 10GE-PON, which is 10.3125 Gbit/s. There were 2.5 Gbit/s and 10 Gbit/s proposals for the XG-PON1 upstream rate. 2.5 Gbit/s upstream rate was selected for specification after careful studying of application scenarios and component cost. The 10 Gbit/s upstream system is still considered as a high cost system with limited application scenarios in the near future.

As an enhancement to GPON, XG-PON1 inherits the framing and management from GPON [6]. XG-PON1 provides full-service operations via higher rate and larger split to support a PON network structure. The baseline XG-PON1 standards have been completed. In June 2010, the transmission convergence (TC) layer and optical network termination management and control interface (OMCI) standards for XGPON1 were consented in the general meeting of ITU-T SG15.

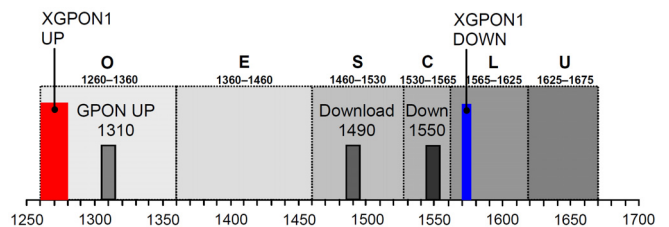


Figure 3. GPON and XG-PON wavelength allocation (video overlay band is supposed to be reused for WDM PON in the future).

Since the downstream window is only 5 nm wide, it will require cooled laser sources and thus should be quite expensive [7]. It is conceivable that this downstream band could be extended beyond 1580 nm for systems that operate on more modern Optical Distribution Network (ODN) infrastructures, and this could enable optical line termination (OLT) optics suitable for outdoor deployment or uncooled operation in an indoor deployment. Such extension must be small, otherwise it will complicate ONU filter design. The upstream wavelength is 1270 nm and window is 20 nm wide, enabling the use of uncooled laser sources under all circumstances, saving on ONU optics costs.

### C. XG-PON2

The FSAN/ITU-T community has still not achieved a consensus concerning the direction for XG-PON2 development. Some experts see a natural progression from G-PON to XG-PON1 and to XG-PON2 with minimal changes in the framing, TC, and management protocols. Others see the 10 Gbit/s upstream as a point for transition to the 10G-EPON standard. This is a subject of ongoing study.

The obvious solution is to retain the 10 Gbit/s downstream paths as implemented in XG-PON1 and to extend the framing structures for the TC layer specified in the XG-PON1 section to support 10 Gbit/s upstream. This would allow for XG-PON1, XG-PON2 and G-PON co-existence on the same PON and would allow the reuse of all of the basic data structures. However, this solution suffers from grave shortcomings. Firstly, it is not clear if fragmentation should be supported in the upstream at these rates and what impacts that would have on the DBA algorithm could be proposed for NG-PON1 systems. In addition, separate ranging windows may be required for XG-PON1 and XG-PON2 to allow the dual rate receiver at the OLT to prepare for the reception of a specific burst at the correct bit rate.

If XG-PON2 follows the 10G-EPON system in some fashion, we then must address the notable gaps in this standard. The XG-PON2 work in the ITU would attempt to fill them. These uncovered topics include: activation, security, protection switching, dynamic bandwidth allocation, and management.

### D. Ethernet PON

EPON standards are being developed in the Institute of Electrical and Electronics Engineers (IEEE) 802.3ah Task Force [8]. The Ethernet in the first mile (EFM) task force of the IEEE 802.3 standards committee published standards that included a passive optical network (PON) variant in 2004. The protocol used in EPON is an extension of IEEE 802.3 and operates at 1 Gbit/s with a reach of 10 or 20 km between the central office and the customer. The architecture is a single shared fiber with an optical splitter. The supported split ratio is 16 users per PON. The system operates in the 1480 nm to 1500 nm band in the downstream direction, and in the 1260 nm to 1360 nm band in the upstream direction. As with 1 Gbit/s EFM Fiber, while not specifically mentioning the wavelength for broadcast video service, EPON allocates its wavelengths to leave the 1550 nm to

1560 nm band open and is capable of supporting a broadcast video wavelength in that band.

Since Ethernet does not utilize a P2MP topology, EPON required the development of a control protocol to make the P2MP topology appear as a P2P topology. This protocol is called the multipoint control protocol (MPCP). Like all PONs, in the downstream direction EPON is a broadcast protocol. Every ONT receives all packets, extracts the Ethernet frames intended for that customer, and discards the rest. As with APON and GPON, transmission in the upstream direction is regulated by TDMA.

### E. 10G-EPON

The 10 Gbit/s Ethernet Passive Optical Network standard (10G-EPON) supports two configurations: symmetric, operating at 10 Gbit/s data rate in both directions, and asymmetric, operating at 10 Gbit/s in the downstream (provider to customer) direction and 1 Gbit/s in the upstream direction. It was approved as IEEE 802.3av standard in 2009 [8].

The main driver for 10/10G-EPON symmetric configuration was to provide proper downstream and upstream bandwidth to support multi-family residential building (known in the standard as Multi Dwelling Unit (MDU)) customers. When deployed in the MDU configuration, one EPON ONU may be connected to up to a thousand subscribers.

The 10/10G-EPON employs a number of functions that are common to other P2P Ethernet standards. For example, such functions as 64B/66B line coding, self-synchronizing scrambler or gearbox are also used in optical fiber types of 10 Gigabit Ethernet links.

## III. OVERVIEW ON TECHNOLOGY DEVELOPMENT

PONs seems to be the most attractive solutions for optical access technologies. All signals are distributed through the optical network from the optical line terminal (OLT) to every end user's optical network termination unit (ONT), which are connected on the same PON branch.

The next-generation (NG) PON should satisfy demands for increasing traffic and higher bandwidths. All future strategies for NG-PON evolution are expected to deploy wavelength division multiplexing (WDM).

Generally, NG-PON technologies are used to subdivide into two categories [9]:

- Evolutionary growth (the so-called NG-PON1). They are supposed to provide improved performance, such as higher data rates, with legacy optical distribution networks and co-exist with legacy PONs.
- Revolutionary change (NG-PON2). Such as WDM-PON, optical code division multiplexing (OCDM), etc., they are supposed to provide enhanced services on new distribution networks.

Current GPONs systems are intended to migrate to NG-PON1 applying identical colorless ONTs. The migration would occur in the same optical distribution network which implies coexistence. The advantage appears in cost saving, easier planning, maintaining and expanding of this network. Here, we mainly focus on evolutionary NG-PON

technologies, XG-PON1 and XG-PON2, that are expected to replace current GPON and EPON solutions in the near- to midterm.

#### A. Deployment Scenarios of XG-PON

A general requirement of NG-PON1 is to provide higher data transmission rates than GPON. On the other hand, it should be done with minimized costs. Thus operators expect NG-PON1 to leverage existing optical deployments. Hence, FSAN/ITU-T specified the NG-PON1 backward compatibility with legacy GPON deployments to protect the initial GPON investments of operators [7][10][11]. The specified NG-PON1 system is called XG-PON1. In an XG-PON1 system, the upstream rate is 2.5 Gbit/s and the downstream rate is 10 Gbit/s (asymmetric line-rate upgrade). In other words the downstream bandwidth of XG-PON1 is four times of that of GPON, while the upstream bandwidth of XG-PON1 is only twice as that of GPON. Since we have a very important result as the ODN in XG-PON1 entirely inherits that of GPON, implying that optical fibers and splitters in legacy GPON systems can be reused in XG-PON1. XG-PON1 also inherits the P2MP architecture of GPON. As indicated in XG-PON1 physical layer specifications, the upstream/downstream wavelength of XG-PON1 is different from that of GPON. Compatibility between XG-PON1 and GPON is achieved by implementing WDM splitter in the downstream at the central office (CO) and a Wavelength Blocking Filter (WBF) at the user side (could be located inside an ONU, between an ONU and an optical splitter, or on an optical splitter) to multiplex or demultiplex wavelengths on multiple signals in downstream and upstream directions. FSAN/ITU-T has proposed two evolution XG-PON1 deployment scenarios to greenfield and brownfield depending on the network maturity:

- Greenfield scenarios can use XG-PON1 to replace legacy copper line systems since they do not have any pre-existing optical fiber deployments. Greenfield scenarios require the deployment of new PON systems, which are straight-forward.
- Brownfield scenarios use coexistence of XG-PON1 with the pre-existing GPON deployments. When migrating to XG-PON1 operators can upgrade ONUs over the ODN batch by batch or all at once. The selection between these two types of upgrades is decided by how long GPON and XG-PON1 will coexist in the same ODN. To achieve a successful GPON-to-XG-PON1 upgrade, the OLT and each ONU must support [ITU-T G.984.5 AMD 1] compliant wavelength plans.

#### B. Coexistence of GPON and XG-PON

FSAN/ITU-T standards are intended to provide the coexistence of GPON and XG-PON and define reserved wavelength plans. The wavelength allocation meets this standard and synergies with IEEE standardization [12].

The wavelength band allocations for GPON are: 1260 nm to 1360 nm for upstream and 1480 nm to 1500 nm for downstream. The neighboring bands are referred to as guard bands separating basic and enhancement bands and preventing interference. G.984.5 standard recommends pre-

installing commercially available low-cost WBFs in GPON ONTs to obtain the required isolation outside the guard bands and to decrease the migration costs. In Figure 4, we propose the coexistence of GPON and XG-PON by implementing two super-separating WBFs in the GPON ONTs. WBFs of steep spectral characteristics should be able to separate the allocated passbands to avoid the interference and moreover to narrow the guard bands. An ideal band-pass has a completely flat passband and thus completely rejects all wavelengths outside the widths of the passband.

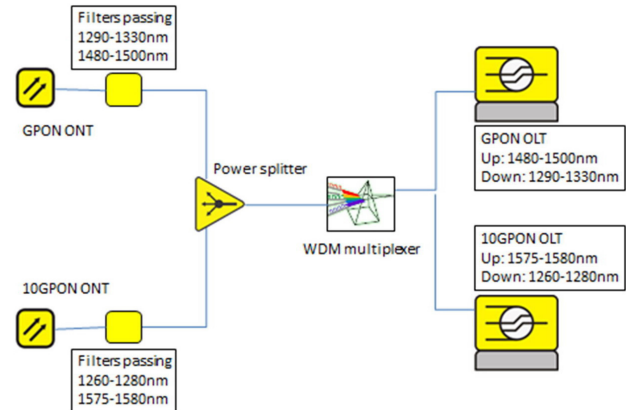


Figure 4. Coexistence of GPON and XG-PON using original ONTs supplemented by WBFs.

Accordingly, the FSAN/ITU-T requirements for the performance of the optical band super-separation filters are:

- at least 32 dB (according to 984.2) insertion loss outside the required passband width and maximum 5 dB insertion loss within the required pass band width of 1290 nm to 1330 nm for WBF upstream and 1480 nm to 1500 nm for WBF downstream,
- guarantee of the filter contrast factor (dB/nm) as high as possible (qualitatively) achieved by steep transmission curves in the vicinity of cut-on/cut-off wavelengths of 1290 nm / 1330 nm and 1480 nm / 1500 nm,
- minimizing severity of production by designing both band-pass WBFs as combinations of short-pass and a long-pass filters in series to achieve the required passbands and to minimize production costs.

#### IV. NEW DEVICES FOR XG-PON DEPLOYMENTS

The evolutionary growth under NG-PON1 is based on the demand of the minimal equipment investments. Thus NG-PON1 should operate with the same infrastructure as GPON. However, current GPON and NG-PON1 coexistence requires wavelength separation of signals to avoid interferences between downstream and upstream channels. Low-cost WBF seems to be able to provide the wavelength band separation to ensure that GPON ONTs can operate undisturbed alongside NG-PON1 deployments. Passive filters based on thin film filter (TFF) technology seems to be the most suitable to use in the NG-PON system configuration with wavelength blocking filters [12].

When deploying XG-PON systems some devices needed to be replaced as shown on Figure 5.

Regarding the comparison of application of WDM filters and tunable lasers for NG-PONs deployment one can suppose that in relatively short-term period the usage of WDM filters seems to be more promising because of smaller costs and more developed technological basis. On the other hand, tunable lasers for NG-PONs are still developing meeting few problems on the temperature control and higher costs. With the lack of a cooling requirement and the electrical power requirements that accompanied by CWDM filters usage, the installation of DFBS-based devices is made possible for outdoor pedestal and strand mount as well as homes [13]. On the other hand, the usage of DWDM filters meets the same problems with high costs on temperature control systems as a configuration with tunable lasers [14].

	GPON	XG-PON1	XG-PON2
OLT			
ONU			
Splitters			
Cables			
ODF			
Filters			
WDM filters			

Should be changed for the next step  
 Could be used for the next step

Figure 5. GPON, XG-PON1 and XG-PON2 backward compatibility.

We also consider different technologies and a number of solutions for the realization of integrated wavelength selective devices for WDM communication systems. Silicon nanowire based technology is a good example of this. This is an attractive way towards highly integrated systems with the capacity for wafer scale mass production compatible with microelectronics. The parameters of the fabricated devices are in many cases not sufficient for practical applications, but the technological improvements are still possible that should allow matching the market demands.

#### A. WDM multiplexer

WDM multiplexer is the optical device, which is required at the central office (CO) under XG-PON deployment [15]. This device combines the GPON, XG-PON, and RF video downstream wavelengths for transmission over a common fiber between the WDM multiplexer and the splitter at the fiber distribution hub. In the upstream direction, the RF video, GPON and XG-PON upstream wavelengths are combined over a common fiber at the splitter hub and demultiplexed at the WDM multiplexer for transmission to the RF translator, GPON and XG-PON OLT respectively.

WDM multiplexers are specified in ITU-T G.984.5. They allow signals from different wavelength channels to be multiplexed into one optical fiber, transmitted together and demultiplexed.

There are several kinds of WDM multiplexer components, which are available nowadays. The first class of such elements based on TFF or fiber Bragg gratings consists

usually of discrete components for each wavelength. The second class is Planar Light wave Circuits (PLCs) also called Photonic Integrated Circuits (PICs) represented mainly by arrayed waveguide gratings (AWGs), but including also more seldom used etched diffraction grating-based multiplexers (EDGs). This is the class that can manage large numbers of channels and treat them in a parallel way and could be considered from aspect of the XG-PON2 deployment long-term prospects. This class can also be integrated with other passive and active components on a common platform.

During the last decade, PLC-based components have greatly improved core network solutions and capacity and are expected to have similar influence on NG access networks. Photonic integration based on silicon platform is now under a very intensive development and due to its compatibility to standard CMOS electronics promises low cost mass production allowing for deployment of FTTx infrastructures more cost effectively than ever before.

#### B. Wavelength Blocking Filter design

As it was already discussed the TFF are suitable low-cost, ONT independent and simple operation candidates for WBFs [12]. TFF is usually made of a sequence of non-absorbing thin films of the thickness that is comparable to the wavelength of light and of materials of high and low refractive index. They should have optical characteristics resistant against temperature changes. The interference of light entering a multilayer structure of a specific number of alternating thin films causes the spectral dependent transfer characteristics of the filter (transmittance or reflectance of optical signal). The number of layers, layer materials, optical properties and thicknesses influence significantly TFF transmission characteristics. Therefore, the spectral transmittance or reflectance of a desired filter can be tailored for a specific application by the number and optical properties of layer used in the design.

#### V. SUMMARY

In addition to the PON and BPON technologies developed by the ITU-T in the past, one can define three important stages in the technology development for the past and the next decades:

- 1 Gbit/s PON era. EPON and GPON concepts proposed in the beginning of 2000s by the IEEE and FSAN/ITU correspondingly were successfully adopted and already emerged as market leaders.
- 10 Gbit/s PON era. The IEEE and FSAN/ITU-T began researching 10G PON technology in 2008 as it was considered to be the beginning of the 10 Gbit/s optical access era. The IEEE released the 10G EPON standard in September 2009. Soon after, the ITU-T launched an initiative to set 10G GPON inheriting the Optical Distribution Frames (ODF) of current GPON and the main standards for XG-PON1 were approved and published in mid-2010. Driven by the growing demand for bandwidth and increasing market competition and given a combination of industry maturity and cost, 10G



PON technology is expected to be commercialized on a small scale in 2013 at the earliest.

- Post-10G PON era. This area is not covered by the leading standards developers and still exists as some concepts and prototypes. The IEEE and FSAN/ITU-T have explored the topic but has not yet arrived at any concrete conclusions, because of large costs and weak relevancy to the market demands. WDM and hybrid WDM/TDM-based technologies may represent the trend, but OFDM, OCDMA and coherent technologies are the likely candidates in the future PON area.

Deployment of new PONs should be optimized by choosing of the correct passive splitting arrangement to decrease the costs on the active infrastructure implementation. Generally, several considerations need to be taken into account when designing the network:

- optimal use of active equipment
- coexistence with current technologies and flexibility to be able to adapt it easily to a future customer distribution
- regulatory needs for unbundling the next-generation access (NGA) networks
- optimizing operational cost due to field interventions

These considerations will result in a number of design rules.

Co-existence of XG-PON1 with current GPON system seems to be the most reasonable to provide with WBFs filters based on TFF technology (on the ONTs side) accompanied by WDM filters to distinguish the signals from different OLTs (on the CO side). WDM systems seem to be the most natural way to interconnect RF CATV and the migrating networks [16]. Physical layer capability of XG-PONs is quite well-known [7][10][11] and could be used as a real guideline for the new networks deployment.

A multi-level splitting system can help to solve the problem of split ratio demands increase corresponding to XG-PON1 deployment. Moreover, XG-PON1 inherits the framing and management from GPON. This is a good advantage of the technology that helps to decrease the deployment costs. Other network elements should be in general changed, replaced, introduced or developed with new network deployment.

In the present paper, we also regarded such technologies as XG-PON2 and tunable lasers that are not considered as a short-term perspective, but also supposed to be an important part of the network deployment in the future. Tunable lasers seem to be a luxury at the moment because of great costs on cooling systems and technological base development. On the other hand, XG-PON2 still does not correspond to the market demands on the upstream channel speed ratio with its also great costs taking into account. Another interesting possibility to improve upstream speeds with less costs using Non-Return-to-Zero (NRZ) coding is still under consideration. This could deliver 5 Gbit/s for not much more cost than the current 2.5Gbit/s optics, and it would of course coexist with the 2.5Gbit/s system (and G-PON) [6].

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