ComReg Document 16/96c

WIK-Consult • Report

Study for ComReg

GPON and TWDM-GPON in the context of the wholesale local access market

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Abbreviations

ALU	Alcatel-Lucent, now Nokia
BSS	Business Support Systems
CAPEX	Capital Expenditure
CO	Central Office
ComReg	Commission for Communications Regulation
CPE	Customer Premises Equipment
CWDM	Coarse Wavelength Division Multiplexing
DOCSIS	Data over Cable Service Interface Specification
DP	Distribution Point
DS	Downstream
DSL	Digital Subscriber Line
GPON	Gigabit Passive Optical Network
Gbps	Gigabit per second
FSAN	Full Service Access Network Forum
FTTB	Fibre to the Building
FTTC	Fibre to the Curb
FTTH	Fibre to the Home
HD	High Definition
HDTV	High-Definition Television
IP	Internet Protocol
ITU-T	International Telecommunications Union – Telecommunication
LLU	Local Loop Unbundling
LTE-A	Long-Term Evolution – Advanced
MAC	Media Access Control
NGA	Next-Generation Access
NG-PON2	Next-Generation Passive Optical Network
NGOA	Next-Generation Optical Access
NRA	National Regulatory Authority
ODN	Optical Distribution Network
OLT	Optical Line Terminator

ONU	Optical Network Unit
OMCI	ONU Management and Control Interface
ONT	Optical Network Terminator
OPEX	Operational Expenditure
OSS	Operational Support Systems
PMD	Physical Media Dependent
PON	Passive Optical Network
PtMP	Point-to-Multipoint
PtP	Point-to-Point
QoS	Quality of Service
SLU	Subloop Unbundling
TC	Transmission Convergence
TDMA	Time Division Multiple Access
TWDM	Time and Wavelength Division Multiplex
UD-WDM	Ultra-Dense Wavelength Division Multiplex
US	Upstream
VDSL	Very High Speed Digital Subscriber Line
VoIP	Voice over IP
VULA	Virtual Unbundled Local Access
WCA	Wholesale Central Access
WDM	Wavelength Division Multiplex
WLA	Wholesale Local Access
XG-PON	Extra Wide Gigabit Passive Optical Network
XGS-PON	Extra Wide Gigabit Symmetric Passive Optical Network

1 Introduction

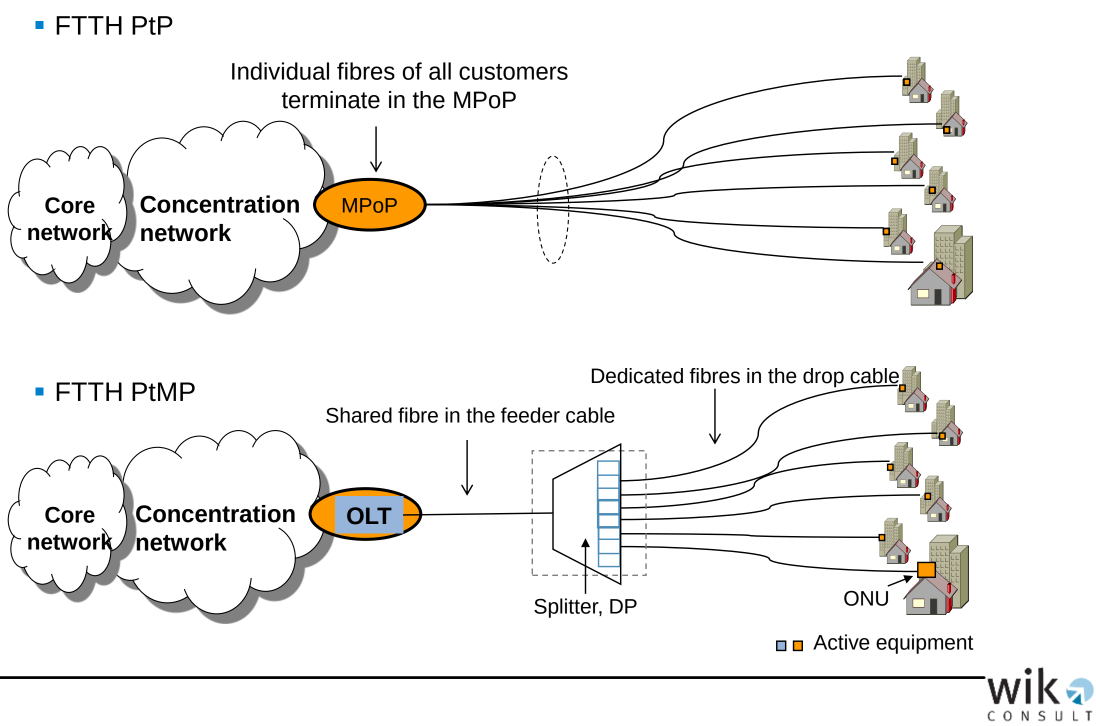
The Commission for Communications Regulation (ComReg), the Irish National Regulatory Authority (NRA), is currently reviewing Market 3 of the recent market recommendation of the European Commission,[1] which for Ireland is split up into the wholesale markets of

a) local access provided at a fixed location (WLA), and

b) central access at a fixed location (WCA).

Market 3a is the successor market of the former Market 4 of wholesale physical unbundled access and today includes the old physical Local Loop Unbundling (LLU) and Subloop Unbundling (SLU), as well as Virtual Unbundled Local Access (VULA) as an active remedy too. VULA is a compromise acknowledging that in many cases the modern FTTC, FTTB and FTTH technologies (Fibre to the Curb/ -Building/ -Home) deployed today do not allow physical unbundling from a technical or economic point of view.

Figure 1-1: FTTH Point-to-Point and Point-to-Multipoint-based Next-Generation Access (NGA) Networks



Source: WIK

1 European Commission Recommendation on relevant product and service markets … of 9.10.2014, C(2014) 7174 final, incl. Annex and Commission Staff Working Document SWD (2014) 298.

This study concentrates on FTTH technologies. Figure 1-1 describes two principal FTTH fibre topologies: fibre Point-to-Point (PtP) and fibre Point-to-Multipoint (PtMP). The first offers individual transparent fibre strands between the end-customer homes and the Metropolitan Point of Presence (MPoP).[2] The second aggregates the end-customer access fibres of each home somewhere in the field with a passive splitter unit onto one single feeder fibre from the splitter to the MPoP. The latter topology also requires some (additional) technical equipment to determine who may send optical communication signals between the end-customer homes and the MPoP in order to prevent signal collision. Such systems are called Optical Line Terminator (OLT) at the central (MPoP) site and Optical Network Unit (ONU) at the end-customer homes. The latter architecture is a widespread FTTH deployment form in Europe and the European incumbent network operators' preferred architecture. The OLT/ONU typically follows the GPON specifications of the International Telecommunications Union (ITU-T).[3] While PtMP fibre topologies require a technology like GPON in order to operate the fibre access network (because of signal collision prevention), PtP topologies allow for many different and individual transmission technologies, and thus are also able to be operated by the GPON technology, if the splitters are located at the central MPoP. One can conclude, therefore, that PtP topologies are technology neutral compared to PtMP topologies.[4]

PtP topologies can be physically unbundled in a manner comparable to the well-practised unbundling of the traditional copper access lines of the past. Also, the economic conditions of viability are comparable. In many cases, SLU (physical unbundling at the street cabinet, FTTC) is already not economically feasible.[5] This is also true for SLU in an FTTH environment based on a PtMP topology, where the coupling point of the home access lines, the splitter, is somewhere in the field. The more the unbundling point moves closer to the end-customer buildings, the less economically feasible it is for the unbundling of the subloop. Thus, one can assume that fibre PtMP topologies with star points close to the end-customer are also not economically feasible (except for very densely populated areas) for fibre SLU, as previous WIK work demonstrates.[6]

The European Commission, and thus ComReg, requires a forward-looking approach in analysing the access inputs. This study concentrates on the specific aspects of fibre PtMP topologies being operated by the GPON technology family as the technology

2 Also often called Central Office (CO) or Local Exchange.
3 ITU-T G.984.
4 For a detailed comparison see: Jay, S.; Neumann, K-H.; Plückebaum, T. "Comparing FTTH access networks based on P2P and PMP fibre topologies", Journal on Telecommunications Policy (JTPO), 8 July 2013.
5 In case of FTTC with a Vectoring technology it also becomes technically no longer feasible, not relevant for this study.
6 Elixmann, D.; Ilic, D.; Neumann, K.-H.; Plückebaum, T. The Economics of Next Generation Access; Report published by ECTA, Brussel, 16 September 2008.
For FTTC see also Analysys report for ComReg: The business case for sub-loop unbundling in Dublin, 20.12.2007, http://www.comreg.ie/_fileupload/publications/ComReg0810a.pdf.

relevant for Europe. It does not specifically include GPON over PtP topologies because these are already physically unbundleable. The upcoming market analysis should consider if and when GPON family products that enable the provision of unbundled "lines" (or better connections) on a per user basis can become standardised and commercially available in the relevant timeframe, based on a PtMP fibre topology as a relevant alternative to VULA. In all cases, the study discusses the underlying Optical Distribution Network (ODN) topology for fibre PtMP.

A technological evolutionary path already exists for GPON, enhancing capacity and usage over XG-PON towards TWDM-PON (Time and Wavelength Division Multiplex) or TWDM-GPON. The study deals with these evolutionary aspects and shall help ComReg to understand how the emerging GPON and TWDM-GPON technology could affect the WLA market and could result in access obligations; this may play a part in the analysis of WLA Market 3a. The study does not cover any VULA aspects of GPON as local layer 2 access, as these are already generally understood and defined by many regulatory authorities.[7] The study also does not cover Market 3b because any NGA technology may allow bitstream access with a central handover, as used in Market 3b.

The next section describes GPON and its evolution as a single wavelength paired system, one for the upstream and one for the downstream direction (Section 2.1). The more advanced products are XG-PON and XGS-PON. In contrast to the older approaches, which support asymmetric bandwidth for the two directions, XGS-PON offers symmetrical bandwidth of 10 Gbps for up- and downstream. TWDM-PON, described in Section 2.2, uses WDM technology (Wavelength Division Multiplex). WDM is an optical transmission technology where not only a single optical beam is used for signal transmission within a fibre strand (also called white or grey light), but several beams on different wavelengths (also called colours) are used in parallel. Such technology requires more focused sender and receiver units than a single beam system and is therefore more expensive. TWDM-PON allows up to eight wavelength pairs in the same ODN.

Section 3 includes an overview of the standards for the GPON technology family up to TWDM-PON (NG-GPON2) and summaries of supplier interviews with Nokia (formerly Alcatel-Lucent), Huawei, Coriant (successor of Nokia/Siemens Network) and ADVA (more of a business customer than a carrier class supplier). ADTRAN, who took over part of the former Nokia/Siemens access network business and also provides GPON and TWDM-PON equipment, did not respond after first contact. The interviews concentrate on the suppliers' view of technology evolution and unbundled use of the different wavelengths in the TWDM wavelength plan.

Service parameters, features and characteristics for controlling the access network in TWDM technology are described in Section 4 in a generic manner. Section 5 compares

7 Plückebaum, T.; Muckhoff, M. Options of wholesale access to Cable-TV networks with focus on VULA, Workshop for ACM, 9 July 2014, https://www.acm.nl/nl/download/publicatie/?id=13474.

physical unbundled LLU and SLU access with wavelength access in relation to the level of control and the ability to differentiate products of competing operators using TWDM-PON wholesale access (wavelength) products.

The network migration from GPON to TWDM-PON is described in Section 6. The first subsection describes the migration process itself, while the second section evaluates the migration scenarios from an economic perspective, taking the operational expenditure (OPEX) and capital expenditure (CAPEX) aspects into account.

The concluding section (7) summarises and highlights the most relevant results of this study.

2 PON technology

2.1 GPON, XG-PON and XGS-PON

The Gigabit-capable Passive Optical Network (GPON) is standardised by the ITU-T Rec. G.984.x. It is a variant of the Passive Optical Networks (PON), based on a Point-to-Multipoint (PtMP) topology (see Figure 1-1). The PtMP topology, typically a tree topology, allows the operator to save some costs associated with network deployment. While in a Point-to-Point (PtP) optical network a single fibre strand is required to carry the traffic between each end-customer and the central office (CO, MPoP), in a PtMP GPON network the feeder fibre going from the Optical Line Termination (OLT), located at the CO, to an intermediate point, commonly known as the Distribution Point (DP), is shared among a given number of users. The DP is based on a passive optical splitter, which splits the signal into 32 or 64 distribution fibres. The distribution fibres connect the DP with the customer premises, i.e. Optical Network Unit (ONU) or Optical Network Terminal (ONT). Therefore, a single feeder fibre is typically shared by 32 or 64 customers.

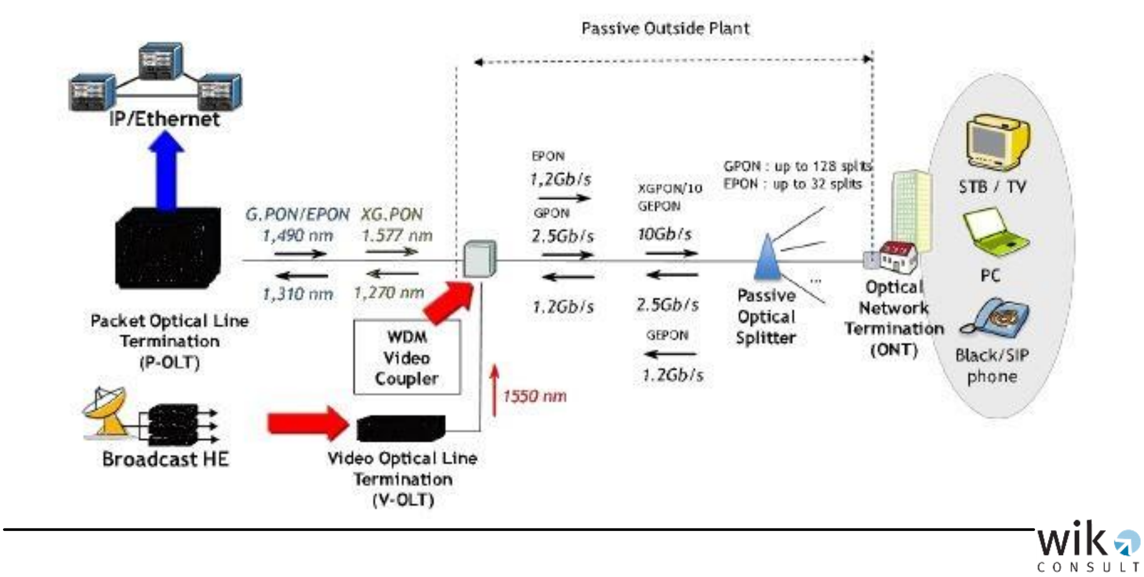
GPON systems operate at two different wavelengths (λ), one in the downstream (DS) and a different one in the upstream (US) direction. On the one hand, the transmission of the data packets downstream (nominal λ=1490 nm) happens in a broadcast manner. All the customer premises equipment (ONU/ONT) connected to the same splitter receives the packets transmitted downstream. If the packets are addressed to all or a subset of CPE, all these CPEs pick the packets from the network. For individual communication, only the single CPE addressed receives the packets. However, the information sent by the OLT is ciphered, and each ONU/ONT deciphers only those packets addressed to it. This mechanism avoids any data security problems that may arise due to the transmission of information over a shared (broadcast) medium. On the other hand, the upstream (nominal λ=1310 nm) data packets of each ONU/ONT are transmitted in a point-to-point manner, implementing Time Division Multiple Access (TDMA) as a medium access control technique. With TDMA, the ONUs compete for well-defined time slots in which the upstream data can be transmitted by the ONUs. Only the ONU assigned a time slot for a dedicated period of time is allowed to transmit upstream within this slot. The OLT is responsible for the TDMA control process, polling (listening) for ONU capacity demand, assigning time slots and addressing the appropriate ONU for downstream communication.

GPON provides an aggregated bandwidth of 2.5 Gbps DS and 1.25 Gbps US. Both bandwidths are shared by the total number of customers connected to the splitter chain, that is, the total number of customers connected to a given port of the OLT at the CO. Assuming 64 end-customers, each one is provided with approximately 40 Mbps DS and 20 Mbps US in the case of full parallel utilisation.

Summarising, the advantages of GPON over legacy systems are listed below:

- There are cost savings with network deployment in comparison to the PtP networks.[8]
- GPON does not require active equipment in the field like FTTC.
- Compared to FTTH, PtP with Ethernet GPON requires significantly less central-sided end-customer access ports, because the end-customers (up to 64) are aggregated on a passive optical splitter. Vice versa, FTTH Ethernet does not require any GPON electronics.
- Fibre access lines allow operators to provide coverage up to 60 km (logical reach), which represents a twelvefold gain in comparison to the typical distance for DSL technologies (circa 5 km).
- There is higher bandwidth per customer than legacy DSL technologies. GPON allows operators to offer a DS aggregated bandwidth of 2.5 Gbps (for up to 64 end-users).
- Since optical networks are not affected by electromagnetic interference or sensitivity regarding humidity, GPON is less fault prone and thus provides better Quality of Service (QoS).

Figure 2-1: Schematic view of a PON (PtMP) network.



Source: FTTH Council (2016)

8 Jay, S.; Neumann, K-H.; Plückebaum, T. “Comparing FTTH access networks based on P2P and PMP fibre topologies”, Journal on Telecommunications Policy (JTPO), 8 July 2013. This demonstrates a 1% difference of total costs between GPON PtMP and PtP topologies.

In the long term, the increased bandwidth demand caused by new services, e.g. High-Definition Television (HDTV), cloud computing, HD video gaming, LTE-A and 5G mobile fronthaul, will create serious doubts about the capabilities of the current technologies such as GPON.

In its Rec. G.987.x document, the ITU-T defines an enhanced technology known as XG-PON (10 Gigabit-capable PON). The objective of XG-PON is the provision of higher bandwidths able to satisfy increased demand. XG-PON provides an aggregated bandwidth of 10 Gbps DS and up to 2.5 Gbps US. It can coexist with the GPON technology in parallel using the same existing ODN and equipment. XG-PON just operates on different wavelengths beside the GPON wavelength. However, the bandwidth upgrade by XG-PON compared to GPON was not sufficiently attractive to many providers, taking into account that migrating the customers requires exchanging the OLT and ONU electronics. Furthermore, many operators complain about poor high bandwidth demand. In addition, the standardisation process already developed systems with even more capacity. A speculative delay for upgrade might be the economic answer to these circumstances. This explains the lack of commercial deployment of XG-PON.

In February 2016 and as an enhancement of the XG-PON technology, the ITU-T approved a new standard for optical access: the XGS-PON technology (ITU-T Rec. G.9807.1). It provides symmetrical bandwidth of 10/10 Gbps US/DS through the use of wavelengths ranging from 1260 nm to 1280 nm US, and from 1575 nm to 1580 nm DS. Since it operates at the same wavelengths as XG-PON, XGS-PON can be implemented on the same ODN together with GPON, but not with XG-PON. In principle, XGS-PON shall replace XG-PON. It represents an intermediate solution between the asymmetrical systems and the Next-Generation PON technology (NG-PON2), being able to satisfy the needs of business customers demanding a symmetrical service.

2.2 TWDM-PON

In 2010, the FSAN and the ITU-T started the standardisation process of the Time and Wavelength Division Multiplexing (TWDM) PON, also known as NG-PON2 (Next-Generation PON stage 2). Although it is also a variant of PON, as shown in the GPON case in Section 2.1, it enhances the performance of GPON, XG-PON and XGS-PON.

TWDM-PON combines the advantages of the Time Division Multiplexing (TDM) PON and the Wavelength Division Multiplexing (WDM) PON networks, meaning that:

- multiple users are efficiently accommodated by using the TDM-PON technology, and

- enhanced total bandwidths, higher security performance and transmission capability over greater distances with smaller optical power loss are achieved by using the WDM-PON technology.

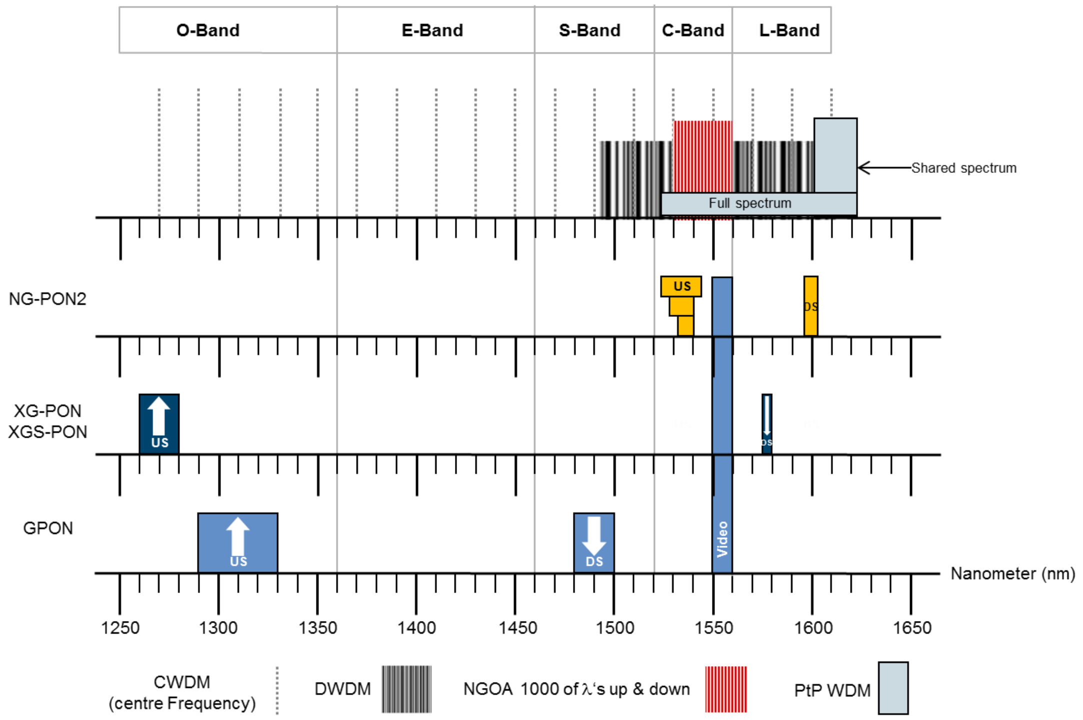
TWDM-PON allows operators to provide up to 80 Gbps DS and 20 Gbps US by using up to eight different wavelengths per fibre. However, the initial TWDM-PON solutions provide realistic bandwidths of 40 Gbps DS and 10 Gbps US stacking four different wavelengths per fibre. Symmetrical services of 40/40 Gbps or 80/80 Gbps are also possible. As in the XGS-PON case, coexistence with legacy systems, i.e. GPON, XG-PON and XGS-PON, is required in order to guarantee smooth migration, customer per customer. Therefore, it is essential to take into account the wavelength planning of the existing technologies.

TWDM-PON operates DS at a wavelength range from 1596 nm to 1603 nm. For US, three different options are defined:

- Wide band: 1524 nm to 1544 nm
- Reduced band: 1528 nm to 1540 nm
- Narrow band: 1532 nm to 1540 nm

An overview of all optical wavelengths used in telecommunications is shown in Figure 2-2.

Figure 2-2: Current wavelength plan of the different optical networks.



Source: WIK

The spectrum allocation (or wavelength planning) and the need for colourless ONUs, which are ONUs that are flexible to use any wavelength without hardware exchange, constitute the two greatest challenges of implementing TWDM-PON. The end-customer premises equipment should be able to tune into any of the NG-PON2 specified wavelengths. The complexity of the transmitter increases, and the receiver has to be equipped with a tuneable filter. This makes the TWDM-PON ONUs more expensive than legacy GPON systems.

Figure 2-2 clearly demonstrates that the wavelength range for GPON is wide and allows for cheaper optics; XG-PON and XGS-PON have the same overlapping wavelength range. Both systems cannot coexist on the same ODN, but each of them can coexist with GPON. NG-PON2 (TWDM-PON) can coexist with GPON and either XG-PON or XGS-PON. The wavelength for transmitting DOCSIS signals for CATV networks (Radio Frequency (RF) at approximately 1550 nm) does not overlap with any other wavelength of these access networks. However, there is some overlapping with the metropolitan and wide area WDM systems (DWDM, CWDM), and also with DWDM-PON and PtP WDM, which is part of the TWDM-PON standardised frequency ranges, defined for Point-to-Point wavelength use (e.g. for business and carriers-carrier customer use) (see Section 3.2).

3 Status, ecosystem and deployment of PON technologies

3.1 GPON, XG-PON and XGS-PON

GPON technology appeared as a remedy to fulfil the gigabit service requirement identified by FSAN members. The key requirements for GPON were:

- 1 Gbps capacity,
- full service support, for example voice, Ethernet, leased lines, and
- IP services-oriented.

Proposed by the standardisation body Full Service Access Network Forum (FSAN) in 2001, GPON was standardised by the ITU-T in its G.984.x series. The first round of the standardisation process was finished in 2004, which served as a basis for first deployments. However, since 2004, the GPON standard has been revised and amended. The G.984.x series includes the following documents:

- G.984.1 – General requirements, approved in January 2003. This document was superseded by a new version in March 2008, with two amendments in October 2009 and April 2012 respectively.
- G.984.2 – Physical Media Dependent (PMD) layer, approved in January 2003. Amendment 1 in February 2006, and amendment 2 in March 2008.
- G.984.3 – Transmission Convergence (TC) layer, approved in February 2004. As in the G.984.1 case, this first approved document, together with the various amendments developed until 2012, was replaced by a new document in January 2014.
- G.984.4 – GPON ONU Management and Control Interface (OMCI), approved in 2004. This document was superseded by a new version in February 2008. Amendments to the new version were published by the ITU-T between its approval and July 2010 in order to add new services and interfaces to the PON system.

In addition to the abovementioned standardisation documents, two more documents were also published by the ITU-T. The G.984.5 standard, which defines an increased bandwidth for GPON by means of WDM overlay, was first approved in 2007 and amended in 2009, and version 2.0 was then approved in May 2014. The G.984.6 document defining the reach extension of GPON systems from 20 km to 60 km was approved by the ITU-T in 2008.

By definition, GPON supports different bit rate options including symmetric bit rates of 622 Mbps or 1.244 Gbps. The maximum asymmetric bit rate and also the most commonly implemented bit rate of 2.5 Gbps DS and 1.25 Gbps US with a maximum split ratio of 1:128, typically 1:64 or lower in real implementations, is defined by the ITU-T in initial G.984 series.

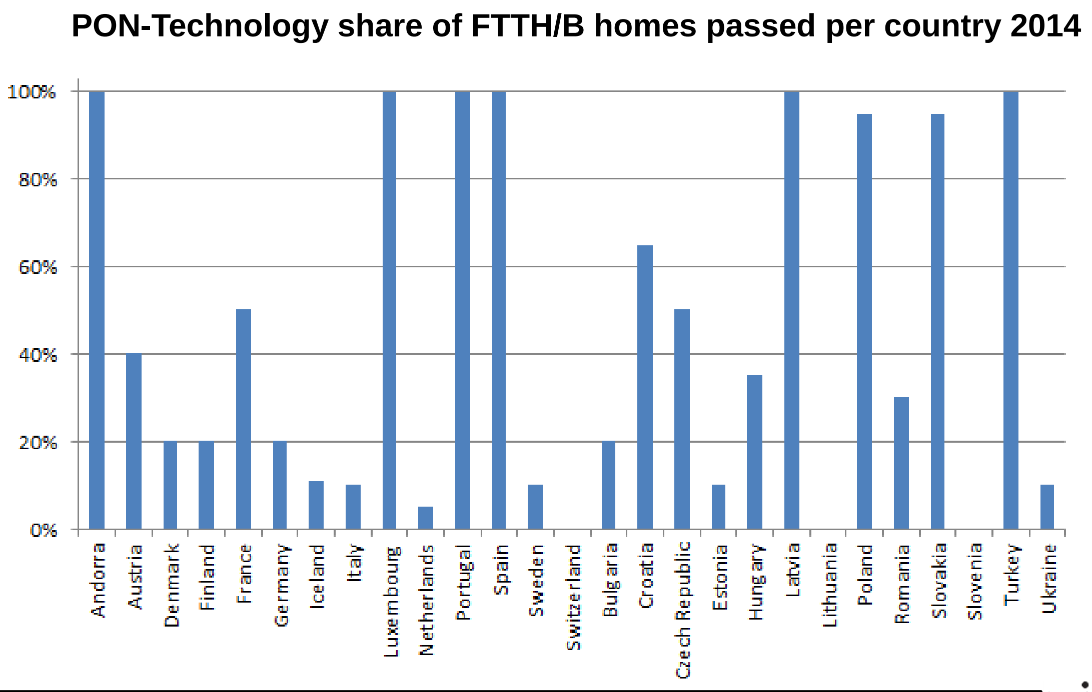
First deployments of GPON were carried out in September 2006 with mass deployments in 2007. GPON is one of the most deployed technologies worldwide today, together with Ethernet PON (EPON), which is mainly deployed in Asia and is more or less irrelevant for Europe. GPON is widely deployed in Europe and North America, where the majority of the largest network operators base their FTTx deployments on GPON technology. Moreover, GPON deployments and/or pre-commercial deployments have been identified in other regions, e.g. South America, Asia and Australia (Figure 3-1).

Figure 3-1: GPON deployment worldwide (2010)

Source: ITU-T (2010)

For many European countries, the PON technology is prevalent (see Figure 3-2).

Figure 3-2: Share of PON technology in FTTB/H homes passed in Europe (2014)



Source: IDATE World FTTx Database (2014)

The FSAN and the ITU-T began researching XG-PON technology in 2008. XG-PON technology is also known as 10G-PON and Next-Generation PON stage 1 (NG-PON1). The ITU-T developed the standard of the XG-PON technology in its Rec. G.987.x series. As in the case of GPON, the first version of the G.987 standard was approved after the completion of four documents in 2010:

- G.987.1 – General Requirements, approved in January 2010 and amended in April 2012. These documents were replaced by a new version (pre-published) in March 2016.
- G.987.2 – PMD layer specification. The first version was approved in January 2010, the second version in October 2010. It was amended in February 2012, and superseded by an updated pre-published version in February 2016.
- G.987.3 – TC layer specification, approved in October 2010 and amended in June 2012. A new version of the document was released and approved in January 2014.
- G.987.4 – It outlines the architecture and interface parameters for XG-PON systems with extended reach and was approved in June 2012.

XG-PON operates at 10 Gbps DS and 2.5 Gbps US, providing an asymmetrical service to the end-customers. Due to the wavelength plan pointed out in Section 2.1, as well as the compatibility with the already existing GPON passive network pieces of equipment, it can be implemented on top of the legacy GPON network. This type of implementation requires a WDM filter at the central office (exchange), enabling the coupling of the XG-PON optical (coloured) beams into the ODN.

Despite the characteristics described in the previous paragraph, XG-PON did not attract too much attention after its standardisation. GPON technology is still capable of dealing with the residential and business demands of end-customers, and most operators did not see the necessity of upgrading their networks to XG-PON.

Several trials were carried out worldwide, e.g. in Cornwall[9] (British Telecom and ZTE), Spain[10] (Jazztel and ZTE), USA[11,12,13,] (Verizon with Huawei, Motorola and Alcatel-Lucent equipment), and Portugal[14] (Portugal Telecom SGPS SA and Huawei). However, XG-PON1 has been commercially deployed only in a few networks, e.g. in China. Therefore, real mass deployment of XG-PON has not occurred yet.

In pursuit of increasing the systems' bandwidth, the ITU-T defined a new PON standard offering symmetrical bandwidth of 10/10 Gbps; as a result, this overtook XG-PON before it could achieve real economic success. The symmetric XG-PON system (XGS-PON) is defined in Rec. G.9807.1, and it was first approved in March 2016. The physical layer is based on the G.987.2 recommendation and the corresponding Ethernet system recommendation (IEEE Standard 802.3). The XGS-PON protocol layer definition follows the G.987.3 and G.989.3 (NG-PON2) recommendations. It operates on the same ODN as XG-PON and reuses the same wavelengths.

Network operators may take advantage of the XGS-PON characteristics in order to carry out a "low-cost" upgrade of their networks and be able to offer symmetrical services to premium business customers demanding this type of service. Moreover, it gives operators the possibility to recover their existing optical fibre network investments.

9 Scarbrough, R.; BT and ZTE Are the First to Deploy XG-PON in a Live Customer Environment, 17 July 2013, http://wwwen.zte.com.cn/endata/magazine/ztetechnologies/2013/no4/articles/201307/t20130717_402288.html.

10 ZTE; Jazztel and ZTE Ready for 10G PON Commercial Launch, 25 February 2014, http://wwwen.zte.com.cn/en/press_center/news/201402/t20140225_418446.html.

11 Hardy, S.: Verizon tests XG PON 10G GPON with Huawei equipment, 17 December 2009, http://www.lightwaveonline.com/articles/2009/12/verizon-tests-xg-pon-10g-gpon-with-huawei-equipment-79551162.html.

12 Lightwave; Verizon's second field trial of 10 Gbps XG-PON FTTP affirms FiOS network design, 23 June 2010, http://www.lightwaveonline.com/articles/2010/06/verizons-second-field-trial-of-10-gbps-xg-pon-fttp-affirms-fios-network-design--97045684.html.

13 Lightwave; Verizon field trials XG-PON2 from Alcatel-Lucent, 28 October 2010, http://www.lightwaveonline.com/articles/2010/10/verizon-field-trials-xg-pon2-from-alcatel-lucent-106064408.html.

14 Huawei; Portugal Telecom and Huawei Jointly Test IPTV Meo Service and 3DTV using 10G-GPON Technology for the First Time in Europe, 28 October 2010, http://www.huawei.com/ilink/en/about-huawei/newsroom/press-release/HW_062663?KeyTemps=10G%20GPON.

As a matter of fact, XGS-PON trials had already been carried out by Jackson Energy Authority[15] with ADTRAN equipment, and Verizon with Alcatel-Lucent equipment in the USA[16] even before the G.9807.1 was finally defined. Nonetheless, commercial network deployments have not yet been identified and are expected to take place in 2017.

3.2 TWDM-PON

TWDM-PON was chosen by the FSAN community as the primary solution for NG-PON2. This solution comprises a splitter-based PtP WDM overlay. There are several reasons to explain the selection of TWDM-PON: wavelength plans, technology maturity, system performance, power consumption, key technologies enabling tuneable ONUs and cost. The ITU-T confirmed TWDM-PON in its G.989 series in 2013, and renamed it NG-PON2.

The standardisation process of TWDM-PON has already finished after the completion of a set of relevant documents:

- G.989 – Definition document: approved in October 2015.
- G.989.1 – General requirements: approved in August 2015. It defines aspects such as architecture, migration, service requirements, physical layer requirements and system requirements.
- G.989.2 – PMD layer and Optical Requirements: approved in December 2014; Amendment 1: Resubmitted for Last Call vote approval. It specifies the architecture of the optical access network, common optical requirements, X/S tolerance for NG-PON2, and TWDM-PON PMD layer requirements.
- G.989.3 – TC Layer/MAC: approved in October 2015.

Table 3-1 shows a summary of the GPON, XG-PON, XGS-PON and TWDM-PON standards defined by the ITU-T.

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15 Hardy, S.; lADTRAN touts 10-Gbps XGS-PON customer trials, 20 March 2016, http://www.lightwaveonline.com/articles/2016/03/adtran-touts-10-gbps-xgs-pon-customer-trials.html.

16 Verizon; Verizon Field Trial of 10/10 Gigabit-per-Second XG PON2 Technology Demonstrates Blistering-Fast Two-Way Speed Over Existing FiOS Network Fiber, 26 October 2010, http://www.verizon.com/about/news/press-releases/verizon-field-trial-1010-gigabit-second-xg-pon2-technology-demonstrates.

Table 3-1: GPON family standards overview

Technology	Standard	Year of standard	Status of deployment
GPON	ITU-T G.984	2003	Widely deployed by the largest operators worldwide
XG-PON	ITU-T G.987	2010	Few deployed networks
XGS-PON	ITU-T G.9807.1	2016	Trials carried out, but not yet deployed
TWDM-PON	ITU-T G.989	2015	Field trials carried out; one live network in the USA

Source: WIK

The TWDM-PON baseline architecture operates at up to four wavelength pairs, expected to be extended to eight pairs in the future (already included in the standards). Each wavelength pair can be configured at different bit rates independent from each other, providing two different bit rate options: (1) asymmetric service up to 40 Gbps DS and 10 Gbps US (4 x 10/2,5 DS/US); and (2) symmetric up to 40/40 Gbps DS/US (4x10/10 DS/US). This feature allows service differentiation and innovation, and enables a multi-service access approach, which represents a significant advantage over the legacy PON technologies. Julie Kunstler (OVUM Consulting) highlights this point:[17]

> *A significant advantage of TWDM-PON is its ability to support different types of subscribers or applications by using different wavelengths and different bit rates on those wavelengths. A CSP can assign a single wavelength to a particular customer, such as an enterprise, or to a particular application, such as mobile backhaul. The ability to simultaneously support more subscribers, more applications, and even network sharing leads to faster network monetization, which is important given the costs associated with building FTTx network.*

Additional general requirements of TWDM-PON are:

- 40 km passive reach (without repeater),
- split ratio of 1:256,
- use of L+ band for DS and C-band for US,
- pay-as-you-grow,
- four different power budget requirements, i.e. 29 dB, 31 dB, 33 dB and 35 dB,
- spectral flexibility, and
- reuse of the optical distribution network.

17 See: OVUM, TWDM-PON is on the Horizon – Facilitating fast FTTx network monetization, 2014.

Pay-as-you-grow

The use of multiple wavelengths requires the installation of colourless ONUs at the end-customer site, and WDM multiplexer/demultiplexer at the OLT site. The end-customer premises equipment, the TWDM-PON ONU, has to be able to tune in to any NG-PON2 specified wavelengths, thus enabling the option to add new wavelength channels when necessary, e.g. new service implementation.

Power budget

TWDM-PON provides higher power budget than legacy XG-PON technology, achieved by using optical amplifiers at the OLT side. These optical amplifiers boost the DS signal and pre-amplify the US signals.

Spectral flexibility

TWDM-PON systems can be classified as static and dynamic,[18] based on the operational wavelengths used in DS and US. While in the static case the wavelengths for DS and US are previously defined and do not change in real time, in the dynamic case the wavelength may change based on operational and communication needs. In a single operator scenario, the spectral flexibility provided by the dynamic case gives the opportunity to rebalance the bandwidth for maintenance work or low-usage hours through what is called wavelength mobility.

Spectral flexibility also allows different operators to share the ODN in a static-based wavelength shared scenario. It requires the arrangement of multiple OLTs. Each operator needs to install its own OLT, which will be able to work with a given wavelength or set of wavelengths. This scheme enables the implementation of a physical unbundling methodology similar to those applied in classical copper-based systems. This aspect is further discussed in Section 5.2 of this document.

Furthermore, spectral flexibility enables the operation of PtP WDM based on those wavelengths that are not used by NG-PON2 or legacy PON technologies (see Figure 1-1). It also allows the addition of new wavelength bands when legacy technologies are no longer in use.

Reuse of ODN

The installation of the WDM Mux/Demux and optical amplifiers at the OLT side, as well as the colourless ONU at the end-customer side, does not modify the basic architecture of the existing ODN. Moreover, the operation wavelengths of TWDM-PON are compatible with those of legacy technologies, presenting no overlapping problems.

18 Abbas, H. S. “The next generation of passive optical networks: A review”, Journal of Network and Computer Applications, Vol. 67, 2016, pp. 53–74.

These issues enable the coexistence of TWDM-PON technology with GPON, XG-PON and XGS-PON technologies.

TWDM-PON can support all broadband optical access applications. Due to the flexibility and the variety of options that might be deployed, in particular the PtP WDM overlay option based on both shared and expanded spectrum, TWDM-PON constitutes a perfect candidate to provide services such as small cell backhauling, cloud radio access network (C-RAN) connecting the Remote Radio Head (RRH) with the Baseband Unit (BBU), and high bandwidth business and enterprises services.

Due to the abovementioned advantages of TWDM-PON over GPON and XG/S-PON networks, this system is drawing the attention of operators and utility companies worldwide. We have identified TWDM-PON trials carried out by Vodafone in Spain,[19] and Energia in Japan.[20] Furthermore, we have recognised one live installation already in operation.[21] TWDM-PON equipment is already available, as announced by one supplier at least: Nokia (former Alcatel-Lucent). Huawei, ZTE and ADTRAN will follow soon.

Nonetheless, we seriously doubt that fast market deployment of TWDM-PON systems will take place. GPON technology is able to satisfy the current residential demand as well as that expected in the forthcoming years, which explains the fact that the majority of operators have skipped XG-PON system deployments, except in a couple of Asian markets in Hong Kong[22] and Singapore.[23] Therefore, we see no real demand for TWDM-PON deployment in the near future, neither from operators nor from end-customers. However, if TWDM-PON installations become reality in the Irish market within the next market analysis period, there might be a technical opportunity to unbundle its wavelengths on TWDM-PON technology for the competitors' wholesale market demand too.

But to be clear, there is already a wavelength unbundling option based on the TWDM-PON standardised wavelength plan that does not require a TWDM-PON system or even implementation, assuming appropriate ONU and wavelength pair administration are

19 Alcatel-Lucent; Alcatel-Lucent and Vodafone conduct first TWDM-PON technology field trial in Europe to deliver super-fast broadband speeds to customers, 22 July 2015, https://www.alcatel-lucent.com/press/2015/alcatel-lucent-and-vodafone-conduct-first-twdm-pon-technology-field-trial-europe-deliver-super-fast.

20 Alcatel-Lucent; Alcatel-Lucent and Energia Communications conduct first field trial of breakthrough G.fast and TWDM-PON technologies for fixed access in Japan, 29 May 2015, https://www.alcatel-lucent.com/press/2015/alcatel-lucent-and-energia-communications-conduct-first-field-trial-breakthrough-gfast-and-twdm-pon.

21 Alcatel-Lucent; Chattanooga Implements World's First Community-wide 10 Gigabit Internet Service, 15 October 2015, https://www.alcatel-lucent.com/press/2015/epb-press-release-chattanooga-implements-worlds-first-community-wide-10-gigabit-internet-service.

22 HKT, Fiber-rich HKT introduces 10G broadband service, 10 February 2015, http://www.hkt.com/About%2BHKT/Press%2Binformation/Press%2BInformation%2BDetail?guid=a6bec5a36437b410VgnVCM1000006a8ba8c0____&language=en_US.

23 M1; (n.d.), Fibre Broadband, https://www.m1.com.sg/business/broadbandmanagedservices/fibre%20broadband#Overview, [Accessed 6 June 2016].

available. One can install several XGS-PON OLTs and colourless ONUs separated by WDM multiplexers according to the standardised TWDM wavelength plan. The operator deploying the PtMP ODN will have to administer the wavelength plan and allocate the wavelength to the different operators, and the operator will also have the responsibility to run the WDM network (monitoring, fault analysis and repair).

3.3 Excursus: DWDM-PON

In February 2010 at the FTTH Council Europe Conference in Lisbon, Portugal, Nokia Siemens Networks presented an Ultra-Dense WDM-PON solution under development. It was part of Nokia Siemens' Next-Generation Optical Access (NGOA) project. Core elements were that the OLT supports 1000 wavelengths and the ONU is self-tuneable, which could adjust its optical receivers to the ultra-dense wavelength, which are all located within the optical C-band (see Figure 2-2). The wavelength and transmitter/receiver units were designed for a 1 Gbps symmetrical communication channel per end-customer, without any shared communication channels. The individual wavelength pairs per end-customer could be unbundled similar to the LLU unbundling, meaning that different wholesale customers could be assigned their own wavelengths. This system proposal and the laboratory installations were presented to operators, regulators and the European Commission in 2010. This current study deals with NGOA in order to explain where this stands today, from a regulatory point of view in relation to ideal PON architecture, because obviously it is not part of the TWDM-PON systems available now.

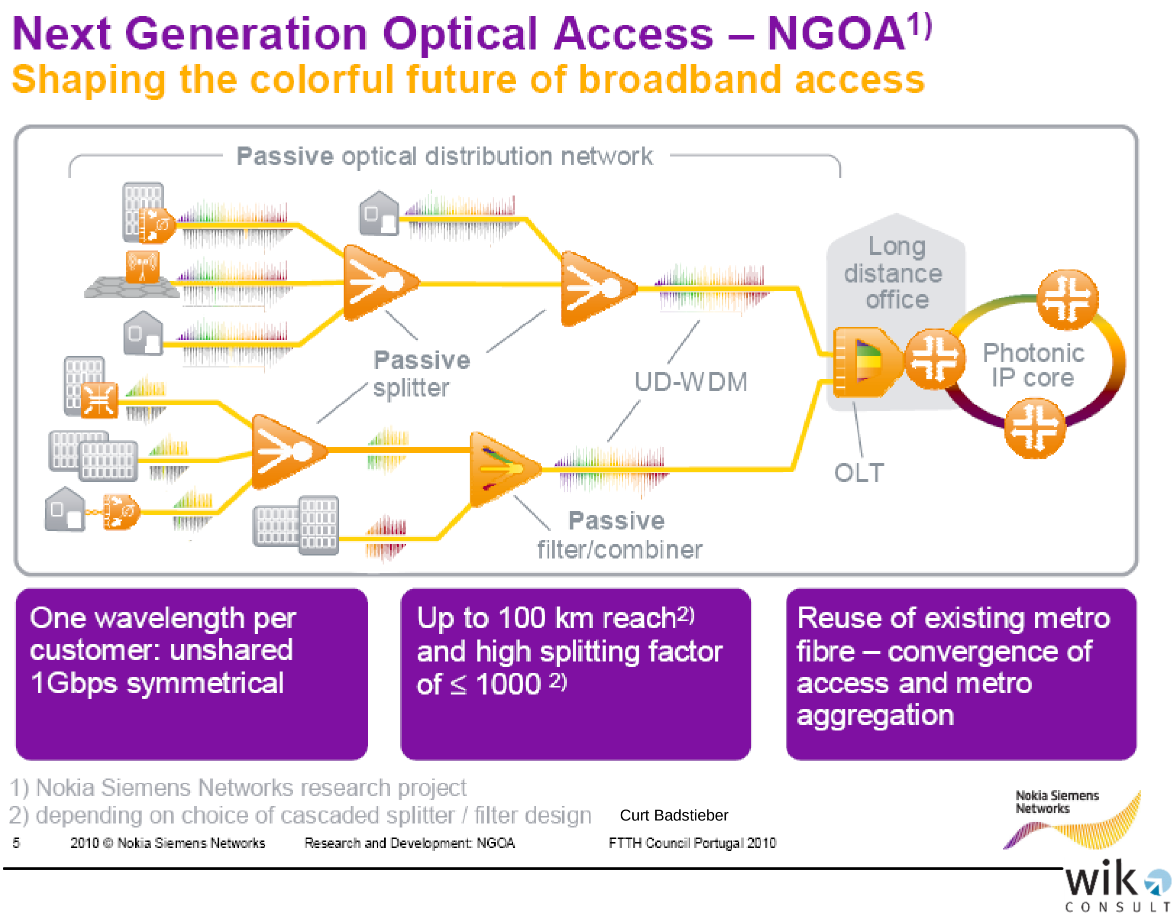
The underlying ODN could be created from existing splitter ODNs (for other PON solutions) and would be upgradable to a maximum distance of 100 km and a cascaded splitter rate of 1000 end-customer ONUs (see Figure 3-3). GPON, XG- and XGS-PON could coexist, as well as NG-PON2 TWDM-PON. NG-PON2 also includes a wider wavelength range for PtP wavelength communication which overlaps with the wavelength range of NGOA. Thus, one could understand that the ideas of NGOA may be resumed within future standardisation work of NG-PON2, sometimes subsumed as DWDM-PON.

While Nokia Siemens decided to sell its fixed network access business to ADTRAN in December 2011 due to financial reasons, the development and patents of its NGOA project were passed on to the core network business unit Coriant. According to Coriant, the development had been stopped due to the high cost of the optical components and the uncertain future of this broadband access market.[24] One could state that this development had been too early for the broadband access market.

24 Supplier interview with Coriant during this study, May 2016.(see Section 3.4)

It is still unclear to what extent these DWDM-PON ideas will fit into a detailed specification of the PtP wavelength plan and systems as proposed and not yet standardised by FSAN.

Figure 3-3: DWDM Network



Source: Nokia Siemens Networks (2010)

The story of the NGOA project makes clear that not all technical solutions ideal from a regulatory point of view with regard to supporting infrastructure competition are successful in an economic sense because of a lack of demand from incumbent operators. This is accompanied by a lack of support in standardisation, where the major incumbent operators and the major suppliers cooperate in defining the technical future without any involvement of regulators or governmental bodies or even user associations.

In order to prevent confusion, the Nokia Siemens Networks company of the past, who sold the relevant system technology to ADTRAN and Coriant, is not the same company as the new Nokia, which was merged at the end of 2015 from the mobile network units of Nokia and Alcatel-Lucent.

3.4 Supplier interview summary

WIK-Consult has conducted a series of interviews with four different optical fibre network equipment vendors, i.e. Nokia (Alcatel-Lucent), ADVA, Huawei and Coriant, and the information gathered from these has led to the conclusions summarised in this section.

GPON arises as the most commonly deployed PON system currently. It is able to satisfy the current residential and business services demand and that expected in forthcoming years. This explains why the deployment of more advanced systems, i.e. XG-PON, XGS-PON and TWDM-PON, has stopped or is evolving very slow.

Commercial deployments of XG-PON technology have already been available for a while, although this system features a relatively low market penetration. As mentioned previously, the current demand of end-customers and the limited advantages of this technology over GPON do not justify mass deployment of this system, especially when new generations with additional features are already available.

All vendors identified the XGS-PON system as an intermediate solution between the XG-PON and the TWDM-PON technologies. The possibility of offering symmetrical service 10/10 Gbps represents a significant advantage over both the XG-PON and the legacy GPON systems, and will be able to satisfy higher bandwidth needs of premium business users. Moreover, the XGS-PON system offers a cheaper deployment alternative than that provided by implementing TWDM-PON. However, in contrast to TWDM-POM systems, XGS-PON is not able to provide bit rate flexibility, which might be a key feature to make operators skip this technology as in the case of XG-PON.

TWDM-PON technology is completely standardised in the ITU-T Rec. G.989, and equipment is already currently available. However, only two pilot networks in Spain and Japan, and a single live network in the USA have so far been deployed. It is not clear when commercial deployments of TWDM-PON systems will be realised to a wider extent:

- Huawei expects 4λ-based TWDM-PON commercial deployments to be available in 2018 or 2019, and 8λ-based TWDM-PON deployments starting in 2020.
- Huawei's point of view coincides with that of Nokia, who expects commercial mass deployments of 4λ-based TWDM-PON systems in the next two or three years.
- Coriant and ADVA did not provide a precise answer about the current and expected status of the deployment of TWDM-PON systems. In their opinion, the commercial deployment of this technology will depend on the needs of end-customers.

- Coriant also stated that there is no intention to restart the NGOA project in the foreseeable future because its core business is core network components, down to regional networks, but not the access network business.

Furthermore, Nokia mentioned the market availability of TWDM-PON-compliant products, and identified a set of possible business cases that justify the investment in TWDM-PON systems, i.e. 3D- and HDTV, 4K- and 8K-video, symmetric premium business customers, and 4.5G and 5G mobile back- and fronthaul.

All suppliers see TWDM-PON systems as being developed with the intention of supporting the future more heterogeneous world of demand being satisfied by one network operator, who could use the different wavelength pairs not only in a bonded manner for increasing the total bandwidth, but even more for structuring the traffic per wavelength pair into different application and/or user classes and in this way operate the wavelength pair sub-networks according to the specific but different qualities demanded. This might include mobile back- and fronthaul, business users, mass market, high-quality video communication up to 3D virtual reality gaming. The option to separate the network capacity by wavelength pairs, enabling different network operators to operate XGS-PON networks in a wavelength unbundled manner and offering a high degree of operating and product definition independently of each other, has not been a core consideration but is an unintended technological side effect. To date, Nokia is the only supplier promoting this option as viable. This may change over time if the fibre infrastructure operators recognise this feature as a chance for better network penetration and better return on investment through additional wholesale business. One should keep in mind that each wavelength pair can be configured and operated more or less independently of each other, thus with in future eight pairs there are also options for dedicated traffic pairs combined with wholesale offers of complete XGS-PON areas.

4 Service parameters for access control in Market 3a

The Wholesale Local Access Market (WLA Market 3a), as defined by the European Commission (EC), was in the past usually provided via Local Loop Unbundling (LLU). This can be transferred to Fibre LLU for PtP topology. For fibre PtMP topologies, physical unbundling of a fibre strand towards the end-customer at the central site (CO, MPoP) is technically not feasible. Such ODN is operated typically by a GPON-type system. Fibre subloop unbundling at the splitter site (somewhere in the field) typically is not economically feasible. Besides the option of providing VULA (Virtual Unbundled Local Access) over the electronic Ethernet interfaces of the OLT, there is a TWDM-PON specific option of unbundling wavelength pairs. One can operate several XG- or XGS-PON networks in parallel over the same ODN, each using a standardised wavelength pair of TWDM-PON, separated by WDM systems (see Section 3.2). This is not physical unbundling. Thus, one might have to check if such a solution meets the generic criteria for VULA in the case of wavelength unbundling.

The EC states that LLU could be replaced by a VULA product which could be considered a virtual counterpart of direct physical line access. The EC recommendation sets out three cumulative criteria for such a virtual wholesale access product to be included in Market 3a:[25]

1. access occurs locally,
2. access is generic and provides access-seekers with a service-agnostic transmission capacity uncontended in practice, i.e. providing guaranteed bandwidths, and
3. access-seekers need to have sufficient control over the transmission network.

The following subsections give information about these criteria in a more generic manner, while Section 5 compares the characteristics of copper LLU and wavelength unbundling.

25 European Commission Recommendation on relevant product and service markets of 9.10.2014, C(2014) 7174 final, incl. Annex and Commission Staff Working Document SWD (2014) 298, p. 42.

4.1 Local handover

Local access, as understood by the European Commission, is one of the key characteristics for Market 3a products. It typically includes traffic handover at MPoP (CO) or street cabinet level. With TWDM-PON wavelength unbundling, the handover will be at the central end of each ODN feeder line, where the central WDM system will be located. The local handover criterion is therefore met.

This criterion allows alternative operators to reuse the infrastructure they deployed already for copper LLU to a wide extent also in case of NGA wholesale access and to produce the same part of the value chain they produced so far, thus determining the service quality and features by themselves. The alternative operators use the local handover to get as close to the bottleneck resources of the incumbent as possible.

4.2 Service-agnostic and uncontended bandwidth

Each wavelength unbundled operator runs its own XG- or XGS-PON access system. It can be as service-agnostic as the incumbent's system, supporting symmetric and asymmetric bandwidth at speeds up to 10 Gbit/s, and enables IP-TV traffic, leased lines and other forms of uncontended bandwidth, which can be determined by each operator, who can select their own transmission systems independently as long as they meet the conditions of TWDM-PON unbundling, i.e. observe and respect the bandwidth range belonging to each TWDM-PON wavelength pair.

Each alternative operator using an unbundling wavelength pair for producing its services is therefore able to design its own products regarding bandwidth and additional service characteristics although it is restricted to the features the XG- or XGS-PON systems support. This restriction has no competitive disadvantage compared to the incumbent operator because the incumbent also has these restrictions. These restrictions are a result of the PtMP fibre topology decision. It is worth noting that this decision has been taken by the incumbent operator – the investor in the broadband access infrastructure – and not by the alternative operators, who might have preferred a PtP fibre topology that would have allowed for an even higher degree of independence.

4.3 Sufficient control over the access network

Each network operator needs as much control over its access network as possible in order to differentiate its services from the competitors, i.e. offer faster service restoration in case of failures. A service cannot be better than the weakest element of its value chain. If an access line breaks, it cannot be repaired faster than the timeframe the wholesale operator offers. Being close to the physical level allows a wholesale seeker to better monitor the access lines and locate failures and identify failure responsibility; thus, it enables the wholesale seeker to design its service quality to a greater extent.

In a TWDM-PON wavelength unbundling access network environment, one operator owns and operates the ODN with the splitters, typically located in the field, and operates the WDM systems, which subdivide the optical TWDM-PON wavelength plan into its separate upstream and downstream wavelength pairs. Operating on such wavelength pairs is pretty close to the physical transmission medium, the fibre. Each wholesale-seeking operator using one or even several of these pairs can operate its own and independent XG- or XGS-PON system and the associated (colourless) ONU. Thus, there is some dependency on the wholesale-selling wavelength operator, who is also responsible for the underlying production quality of the ODN. This includes adding new buildings or homes, administrating and allocating the bandwidth ranges, and operating and maintaining the ODN and wavelength network. The OLTs and associated ONU/ONT are determined and operated by the wholesale operators who also operate their own service provisioning and XG- and XGS-PON management systems. It might be worth thinking about whether each of the wholesale XG- or XGS-PON operators should also have the same capability as the ODN operator regarding monitoring the complete optical spectrum of the ODN in order to analyse if any of the OLTs (or the ONU or even a third-party component being introduced into the ODN, be it intentionally or otherwise) are disturbing the transmission of the wavelength pairs by optical signals, thus interfering and colliding with the wavelength ranges of the TWDM-PON wavelength plan. The ODN operator may also operate a fibre access line supervision system, and also in this case the XG- or XGS-PON operator might have an interest in monitoring its access lines by themselves.

5 LLU, SLU and wavelength unbundling

In 1988, the EU started to liberalise different segments of the telecoms market, which culminated in 1998 with the liberalisation of the voice service and the access network infrastructure. National Regulatory Authorities (NRA) had to establish a fair competitive market situation. The NRAs have defined mechanisms that allow alternative operators to access the network of the incumbent operator. This allowed new entrants in the telecom market and boosted competition. Competition implied a reduction in the end-customer prices, a wider ream of services, better quality of service, and it promoted investment in technology evolution.

This section provides an overview of the classical types of access to the incumbent's network: (1) physical unbundling in legacy copper-based DSL systems, i.e. LLU and SLU; and (2) Next-Generation PON networks (TWDM-PON) based on wavelength unbundling. Finally, a comparison between these types of network access is carried out in order to assess whether wavelength unbundling could introduce infrastructure-based competition as the pure copper LLU did before.

5.1 Unbundling in classical copper networks – LLU and SLU

The physical LLU constitutes a wholesale product based on an obligation of the incumbent operator to lease telecom facilities concerning the local loop. The local loop, also known as "last mile", comprises the wires and the passive equipment that connect the CPE to the local exchange. These facilities grant a new entrant operator access to the incumbent's local loop, and give it the possibility to provide broadband services to end-customers.

LLU can be classified as full and shared local loop unbundling. The differentiating point between these two cases is the landline bandwidth. On the one hand, the new entrant operator has access to the full frequency band, which allows them to provide both the telephone and broadband services. On the other hand, the new entrant only has access to the high-frequency band, enabling them to offer broadband services (incl. VoIP), while the lower-frequency band remains with the incumbent. Therefore, in the shared LLU case, only broadband services can be offered.

SLU is defined by NRAs as an alternative methodology to grant access to the last mile. It provides access to the segment of the network from the CPE at the end-customer's home to an intermediate point, known as the street cabinet, placed on the side of pavements. While this type of access does not seem to present relevant advantages over LLU in order to offer telephony services, it is important for fibre to the curb (FTTC) networks. In this type of network, fibre cables connect the local exchanges to the street cabinet, and copper cables connect the street cabinet to the CPE. The copper lines to the end-customers are therefore significantly shorter. This network architecture thus enables higher bandwidth services, e.g. VDSL, VDSL2. This represents a relevant competitive advantage and attracts the attention of new entrants too.

These types of physical access allow a new entrant to deploy any non-interfering equipment on both the network side and the end-customer side. The possibility to access and manage both the CPE and the equipment relevant to the broadband service enables service differentiation and innovation, e.g. provision of any technically feasible speed (including symmetric services for business customers), new functionalities such as multi-VLAN, and upgrades from the classic DSL service to Dual- or Triple-Play service. This feature is a key point to be considered by new entrants in order to attract end-customers. Moreover, offering a wider range of differentiated services instead of replacement services already provided by the incumbent will assure the survival of new entrants. On the other hand, the incumbent is to some extent forced to analyse the services offered by new entrants and improve their own network/services to be able to provide an equivalent quality of service to their end-customers.

Service differentiation and innovation are very attractive for new entrants. However, NRAs are responsible for guaranteeing that the access will be non-discriminatory, i.e. equal treatment of operators regarding access and with respect to offering services and access to information on conditions not worse than applied internally. If there is discriminatory access to the incumbent’s network, other wholesale products, e.g. bitstream, might be preferred by new entrants. This type of product does not allow service differentiation and innovation, which limits the improvement of the quality of offered services and reduces investment in technology evolution.

Based on the characteristics of the physical unbundling access described in this section, it can be concluded that LLU and SLU boost competition and thus lead to improvement in the quality of the services offered to end-users.

5.2 Wavelength unbundling

The aim of this study focuses on the analysis of the Next-Generation Access (NGA) networks, i.e. GPON, 10-Gigabit-capable PON (XG-PON), together with its symmetric variant (XGS-PON) and the Next-Generation PON stage 2 (NG-PON2), in particular the TWDM-PON technology.

As introduced in Section 1, there are two topologies that might be used to deploy fibre to the Building (FTTB) and fibre to the Home (FTTH) networks:

(1) Point-to-Point topology (PtP), and

(2) Point-to-Multipoint topology (PtMP).

PON networks are by definition PtMP, FTTH-based networks. In this case, the central office (MPoP) is connected to an intermediate star point, a splitter through a single fibre strand, which combines the traffic of a group of up to 64 access lines.[26]

There are several options for locating the splitters in the ODN:

- in the basement of the customer building, for example with multi-dwelling units,
- close to the end-customer buildings,
- in a cascade, starting at the building with a first splitter and using a second close to a group of buildings, aggregating the access lines to the upper limit of 64 lines being splitted over all splitters in a line, or
- in the central office, using a fibre PtP topology between the customer premises and the central office, but concentrating the access lines with splitters in a passive manner to significantly fewer fibre strands, which then are connected to the electronic communication ports of the OLTs, allowing the optimisation of the splitter and electronic port utilisation.

The physical access described in Section 5.1 applies only to classic copper networks and hybrid copper-fibre networks (FTTC). In case of NGA networks based on GPON, XG-PON and XGS-PON technologies, this type of unbundling could only be realised at the splitter location closest to the end-customer. Collocation at that point is typically not economically feasible for new entrants intending to access the fibre distribution lines in an unbundled manner.

VULA has been defined by the NRAs as an alternative methodology to grant access to the incumbent's network and service differentiation. However, since VULA is out of scope of this study, it will not be further described.

Although PON networks were not designed for unbundling, alternative unbundling options have been identified for GPON and XG-PON networks. Analysys Mason[27] specifies two main types of unbundling based on (1) fibre "flexipoints" and (2) wavelengths. In its report, Analysys Mason defines and models up to six different feasible unbundling scenarios:

(1) Base Scenario: End-customers separated by layer-2 protocols

(2) WDM-PON: Separation of end-customers based on wavelengths

26 The upper limit of access lines may become larger according to more modern technologies and attenuation plans (e.g. 128, 256).

27 See: Analysys Mason, "Competitive models in GPON", 2009.

(3) Field flexipoint, single fibre: GPON network deployed per operator, feeder fibre and splitter per operator, flexipoint located in the field (cabinet location), and a single fibre between the cabinet and the end-customer

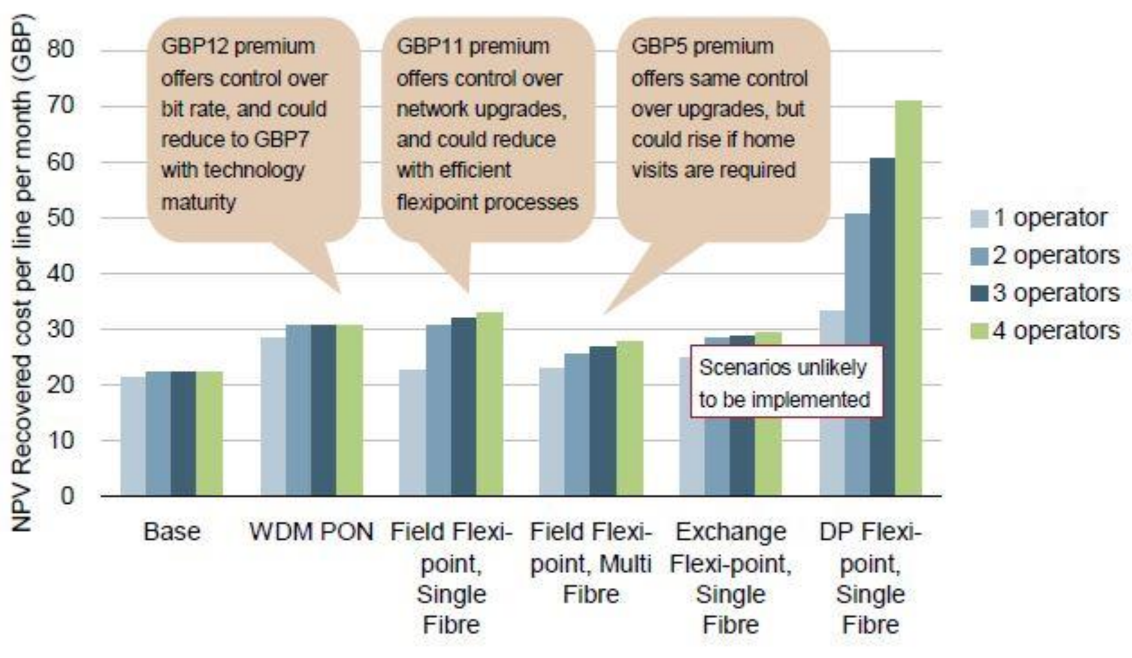
(4) Field flexipoint, multi-fibre: Similar to the previous case, but with the installation of multiple fibres between the cabinet and the end-customer (traditional multi-fibre approach)

(5) Exchange flexipoint, single fibre: Similar to (3) with the flexipoint located at the exchange

(6) Distribution Point (DP) flexipoint, single fibre: Similar to (3), but the flexipoint is located deeper in the access network in the DP

Scenarios (2), (3) and (4) are presented as economically feasible and worthy of further investigation. Figure 5-1 shows the Net Present Value (NPV) recovered cost per line of the scenarios investigated.

Figure 5-1: Overview GPON unbundling NPV of the Analysys study



Note: results for one operator in the unbundling scenarios show the cost of deploying the infrastructure for multiple operators (e.g. flexipoint cabinets) but where only one infrastructure operator is active. In reality, a market scenario with only one active infrastructure operator would be equivalent to the Base scenario.

Source: Analysys Mason (2009)

With current knowledge, WIK does not share Analysys' view of the likelihood of implementation: among other things, the supplier interviews conducted for this current study showed that there are numerous GPON installations based on scenario (5), where the access network topology is PtP and the flexipoint is at the CO. There are also installations at the DP (scenario (6)), preparing for ONUs operating with G.fast and XG.fast instead of VDSL.

A second study dealing with wavelength unbundling has been developed by R. S. Penze.[28] The purpose of the study is to increase the ODNs powered by a single feeder fibre without modifying the bandwidth per end-customer. The proposal is based on the use of Coarse Wavelength Division Multiplexing (CWDM). Four GPON in-band wavelength channels are transmitted over the same physical ODN in order to upgrade and extend the reach of the current PON. The GPON OLT and ONU transmitters and receivers do not need any interface changes.

TWDM-PON provides up to 80 Gbps DS and 20 Gbps US by stacking up to eight different wavelengths. Initial deployments will be based on four different wavelengths providing up to 40 Gbps DS and 10 Gbps US. Symmetrical services of 40/40 Gbps and 80/80 Gbps are also possible. The use of different wavelengths defined in the standard of TWDM-PON was initially not thought to enable unbundling, but to increase the bandwidth offered to the end-customer and to separate traffic classes and/or customer groups from each other, e.g. allowing the separation of mass market fixed network customers from mobile front- or backhaul, and high-end business customer access. However, this wavelength stacking also enables the differentiation of operators on a wavelength basis.

Alcatel-Lucent (ALU, now Nokia) defines three different layers in an FTTH-based network:

(1) the passive infrastructure layer comprises physical elements required to deploy the network, e.g. ducts, sewers, dark fibre, splitters, poles, trenches,

(2) the active network layer includes the electronic network equipment, together with the business and operational support systems, and

(3) the retail service layer covering residential, public and business services.

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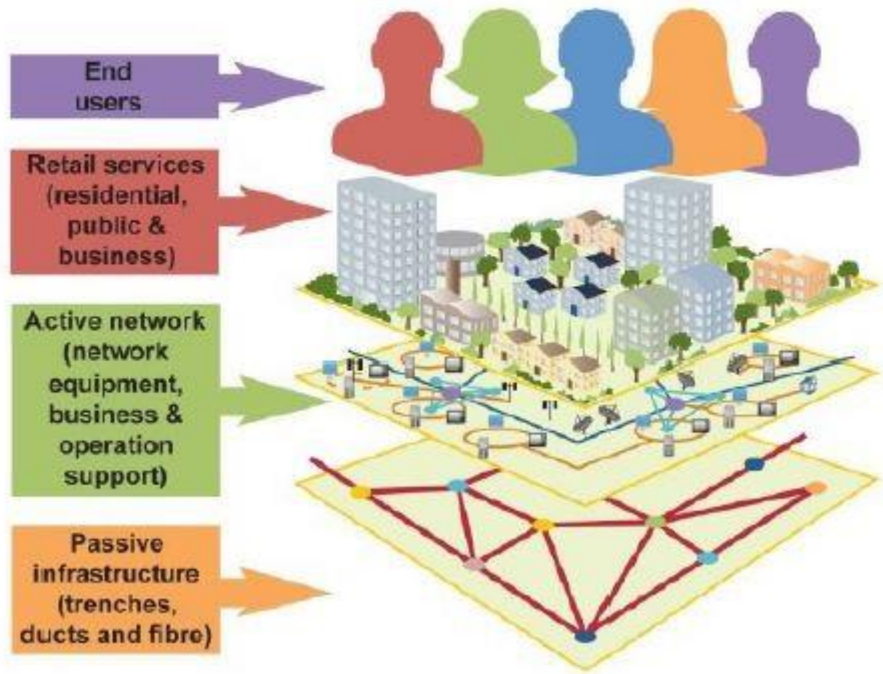
28 See: R. S. Penze, "Upgrading and Extending PON by Using In-Band WDM Overlay", Journal of Microwaves, Optoelectronics and Electromagnetic Applications, 2012, proof of concept given in a pilot network.

Figure 5-2: Layer scheme proposed by ALU (Nokia)



Source: Alcatel-Lucent (Nokia)

Three different types of unbundling[29] in TWDM-PON are defined according to the layer that is unbundled:

(1) “Passive Sharing” or unbundling at the bottom layer: this requires the installation of active equipment by each OLT that has access to the shared ODN. Each operator runs the network at different wavelengths.

(2) “Active Sharing” or unbundling at the middle layer: an operator, which might be the incumbent, provides new entrant operators with the active equipment required to operate the network. As in (1), a different wavelength or set of wavelengths is assigned to each operator.

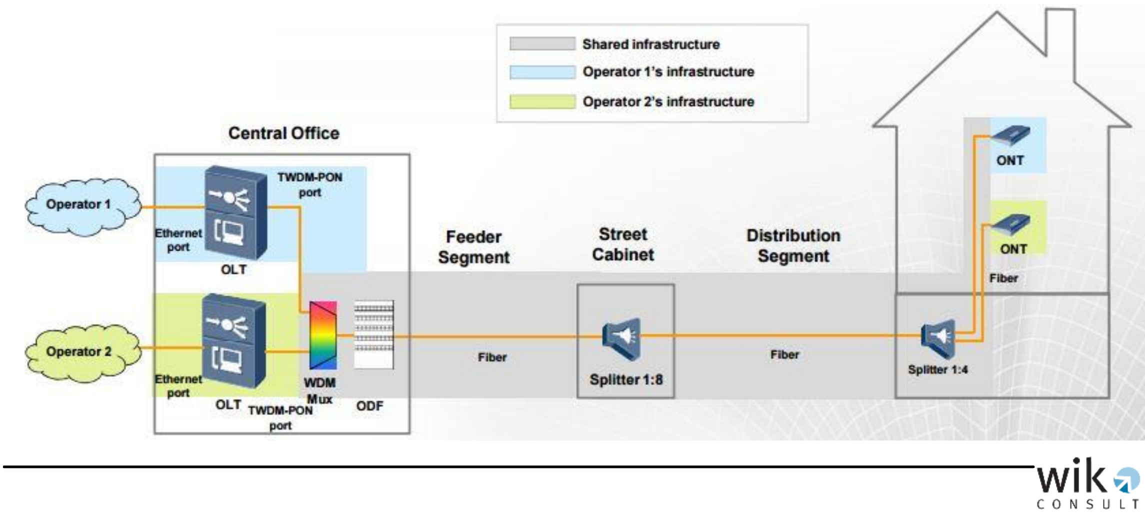
(3) “Full Separation” or unbundling at each layer: each layer is deployed and maintained by a different organisation.

29 Pesovic, A. The Bright Future of TWDM-PON and Wavelength Unbundling, 22 February 2016, http://www.lightwaveonline.com/articles/2016/02/the-bright-future-of-twdm-pon-and-wavelength-unbundling.html.

This study focuses on the “Passive Sharing” defined by ALU (Nokia). This type of unbundling requires the installation of an OLT by each network operator sharing the ODN, which operates at different wavelengths/set of wavelengths. This is known as wavelength unbundling.

This type of wavelength unbundling differs from the WDM-PON unbundling presented by Analysys Mason in its 2009 report in the separation scheme. While the WDM-PON unbundling separates the end-customers by wavelength,[30] the wavelength unbundling of TWDM-PON establishes several XG- or XGS-PON networks for the incumbent and the alternative operators, also making use of the same fibre but overlaying the access networks to all end-customers by using different wavelengths (see Figure 5-3).

Figure 5-3: Schematic view of wavelength unbundling in TWDM-PON systems



Source: Huawei (2014)

In this case, CWDM-coupler systems have to be installed between the OLT and the splitter in the central office on any existing ODN. This physical wavelength unbundling gives access for a limited number of wholesale access-seekers on the basis of the TWDM-PON wavelength plan. Each operator would use its own (white colour) XG- or XGS-PON OLT. Such an approach would require coordination of the wavelength plan on the ODN, and also coordination of the ONUs’ wavelengths such that each ONU can only access the wavelength pair of its service provider.

Wavelength unbundling is presented by ALU (Nokia)[31] as a suitable physical unbundling access methodology for TWDM-PON networks. It offers similar advantages to those provided by the LLU and SLU, e.g. it helps operators to secure additional

30 As does NGOA (see Section 3.3).
31 See footnote 29.

revenue from wholesale products, reduces investment costs for the new entrant, promotes competition, and boosts investment in fibre network deployment.

Since each wavelength pair can be configured to work at different bitrates, symmetric 10/10 Gbps and or 2.5/2.5 Gbps, and asymmetric 10/2.5 Gbps, each operator can configure its own wavelength/s according to the services offered and the needs of the end-customers. This mechanism allows for service differentiation and innovation, and gives operators new revenue opportunities.

5.3 Comparison

In Sections 5.1 and 5.2, the unbundling possibilities for both classic copper networks and NGA FTTH/FTTB-based networks have been described. Moreover, the most relevant characteristics of the different unbundling options have been presented.

The physical unbundling access in legacy copper-based DSL systems has been extensively used in regulation to promote competition. This level of competition based on LLU is only possible for FTTH NGA-based systems if SLU (in case of PtMP topologies) and/or fibre LLU (in case of PtP topologies) are implemented and offered as wholesale products. However, PtP is rarely deployed by the incumbent network operators and SLU is not economically feasible for new entrants due to the high investment costs to connect to the splitter location (cabinet or even DP) and the poor scale effect of customer aggregation (low number of customers). Consequently, there is no chance for comparable success of physical unbundling in NGA networks.

The new entrant operator gains full access to the incumbent's network and controls all the broadband-relevant equipment in the copper LLU. The new entrant operator connects directly to the copper wires located in the exchange, and is allowed to install any non-interfering CPE at the end-customer side, which enables service differentiation, e.g. parental control and firewalls. As indicated in Sections 3.2 and 5.2, TWDM-PON also allows the same type of service differentiation and innovation based on the configuration of the wavelength/set of wavelengths operated by each operator. Furthermore, the wavelength unbundling defined for TWDM-PON is based on the arrangement of one OLT per operator at the exchange level. It can be concluded that this type of wavelength unbundling replicates the LLU in terms of network control and service differentiation and innovation.

If an end-customer intends to exchange its access network provider (end-customer portability), for LLU, the CPE of the customer would need to be replaced by that of the new operator if it is operator-owned or includes operator-specific characteristics and is unable to be used in the new operator's network. This is also true if an end-customer wants to change network operator in case of wavelength unbundling. However, assuming that there are no interoperability conflicts between the OLTs of the new operator and the ONU installed at the end-customer side, this switching might be realised directly from the exchange by simply changing the wavelength of the end-customer. This is the case in unbundling scenario number (2) “unbundling at the middle layer”, mentioned in Section 5.2, or if the ONU is equipped with tuneable receiver and transmitter units and if the retuning can be triggered.

6 Network migration

While the PON networks can also be operated on the technological neutral PtP fibre topology, this study concentrates on PtMP topologies as the more problematic case regarding network unbundling and infrastructure-based competition. Nonetheless, the results of this section regarding migration to modern PON-based network architectures (TWDM-PON, NG-PON2) can be directly applied to PtP fibre topologies too. A PtP topology would allow for some complexity savings, as expressed at the end of this general introduction into migration and before we detail the different migration paths in Section 6.1.

It cannot be assumed that a European country today is completely covered by an FTTH-based fibre access network. Fibre roll-outs are still happening today and will also happen over the next ten years or even longer. An efficient design of a fibre PtMP topology strongly depends on the system capabilities operating it. Section 2 describes the different extensions of the OLT areas (20 – 60 km) and the different numbers of end-customer access lines a splitter (cascade) might have. There is therefore typically no option for backwards compatibility of the TWDM-PON-suited PtMP fibre topology being used by the old GPON technology, but compatibility is available in the reverse direction. This means that an operator deploying an FTTH PtMP network today has to decide which of the PON technologies to use to start network operation: the old GPON, the new XG- or XGS-PON or the brand new TWDM-PON systems. This decision will determine the migration steps for a network deployed today.

Migration from GPON to TWDM-PON for a network optimised for GPON in a PtMP topology covers all migration steps and considerations required for network upgrades. Therefore, the study starts its migration considerations with GPON and the different upgrade paths.

As already shown in Section 2, Figure 2-2, the wavelength plan is organised for GPON, XG-/XGS-PON and TWDM-PON existing in parallel on the same physical optical network, including with RF for CATV. There is no need to exchange any fibre or splitter. The systems may be coupled into the PtMP fibre plant at the central office by WDM systems/couplers, and the end-customers have to be provided with the appropriate ONU.

The coexistence of the wavelengths allows different PON technology generations to operate in parallel (except XG- and XGS-PON). This means there is no need to actively migrate end-customers from one system to the other, but the operator can try to pull them by up-selling. If the end-customers are migrated completely in the future, this requires both platforms to operate in parallel. The GPON customer access lines do not save splitter space for the XGS-PON platform. After migration, all the access lines will operate with the XGS-PON platform. The network load will shift from the GPON OLTs to the XGS-PON OLTs over time, using the same access lines and splitters. There is no chance to increase the XGS-PON OLT number or capacity according to the increasing number of XGS-PON customers. The OLTs have to be provided fully in parallel from the beginning.

Each migration towards new network technologies requires upgrades in the related OSS and BSS systems. A process flow is therefore required to provide new services for end-customers on the new platform, monitor them during their lifetime and cease them. It also needs an option to migrate a service from the old to the new systems, ideally without major outage times. It may be that one (low-speed) service can be produced on both network platforms. Because of the coexistence of the platforms, one may have to decide how to deal with that: should old customers remain on the old platforms while new customers are put on the new one? When will the old platform be actively switched off? If the existing OSS and BSS systems can be simply expanded by some services and additional platforms, the adaption may not be too expensive. It may be easier or even very smooth if both platforms are from the same supplier. The BSS and OSS aspects have to be taken into account in any such migration processes, but cannot be qualified or even quantified in a study like this.

If the fibre network topology is PtP, operated by GPON, many of the considerations would not be required because the underlying fibre topology allows for the connection of all end-customers to their appropriate OLT. A reconfiguration of the ODN could be made in a quick and simple manner at the CO location. Thus, during migration, the number of OLTs could be adapted to both, the decreasing number of end-customers for GPON and to the increasing number of upgrading customers on the XGS-PON.

6.1 Network migration scenarios

1. GPON -> XG-PON
   Starting with an FTTH GPON NGA network with a maximum of 32 end-customers per splitter, the operator could upgrade the ODN by deploying a second, additional OLT in the CO using XG-PON technology. While a GPON feeder fibre typically does not carry more than 32 customers, these fibres may be once again aggregated by a 1:4 splitter in the CO for meeting the 128 end-customer splitting ratio of XG-PON at the CO location. This way, the number of XG-PON OLT could be reduced to a quarter of the GPON OLT. The end-customer ONUs have to be exchanged per customer when upgrading the access technology. There is also a larger probability that the OSS and BSS systems have to be exchanged, at least insofar as they have to be upgraded.

2. XG-PON -> XGS-PON
   Migrating from XG-PON to XGS-PON is not really intended because both technologies operate at the same wavelength range and cannot coexist on the same fibre. Such migration just upgrades XG-PON to symmetric traffic at

10 Gbps, which is not a sufficiently important improvement to justify the system exchange. In any case, such migration would cause longer outage times for exchanging the equipment on the ODN, or the need for a parallel ODN of additional fibre which one cannot assume. Such migration in fact is a dead end. One solution would be to directly migrate from XG-PON to TWDM-PON; the other alternative is to directly migrate from GPON to XGS-PON. Since there have not been many XG-PON deployments so far, direct migration to XGS-PON is the most recommended.

3. GPON -> XGS-PON
   For the sake of brevity, this is similar to scenario 1. The advantage of XGS-PON is its capability of symmetry at 10 Gbps.

4. XGS-PON -> TWDM-PON
   Once again the OLTs and the ONUs have to be exchanged, and the WDM-coupler has to be expanded including the new wavelength ranges of TWDM-PON. There may be another splitter aggregation step upgrading to a splitting ratio of 1:256 by adding an appropriate additional splitter in the CO. The number of OLTs could be reduced compared to the XGS-PON OLT. Depending on how much additional wavelength is required to meet the end-customer demand, serve additional customer groups or serve additional wholesale customers, there is an option to consolidate several former XGS-PON OLTs, so far serving different areas, into one TWDM-PON OLT. It can be assumed that the system suppliers of OSS and BSS systems also offer an upgrade path for their systems in order to support upgrade migration, at an additional cost.

5. XG-PON -> TWDM-PON
   For the sake of brevity, this is similar to scenario 4. The advantage of TWDM-PON is its capability of symmetry at 10 Gbps.

6. GPON -> TWDM-PON
   This direct migration excludes intermediate steps and saves investment in XG- or XGS-PON systems. More detail is given in scenario 4. The degree of splitter aggregation adds up the steps from migration 1 and 4.

Planning the migration steps should take the future bandwidth demand and the expected equipment lifetime into account. It makes no sense to exchange the equipment because of insufficient capacity after half of its lifetime.

The network migration scenarios discussed above do not really cover the options of wavelength unbundling relevant for any Market 3a considerations. Wavelength unbundling comes into the game at any time, independent of the technology deployed. It should happen on the wavelength pairs defined in the TWDM-PON wavelength plan.

These wavelengths then have to be coupled into the existing ODN by WDM couplers and operate beside the other wavelengths. In theory, it may be that the incumbent operator has not yet deployed a TWDM-PON network for its own services, but still operates with GPON or XG-/XGS-PON technology. Coupling a TWDM-PON wavelength pair will not harm the other services, but will be able to coexist. This wavelength pair then is occupied by its whole buying operator and will no longer be available for other services.

6.2 Evaluation of the migration scenarios

This section focuses on the CAPEX and OPEX side of the migration scenarios discussed above.

Migration within the PON technology from GPON to TWDM-PON (NG-PON2) does not require any exchange of the physical ODN. Thus, the investment for the civil engineering infrastructure, which represents the highest share of investment, can be reused with any of the new technologies. This holds for both fibre topologies, PtMP and PtP.

Any migration carries costs, not only for the new systems and their implementation (CAPEX) but also for contacting the customers and migrating them to the new services (OPEX). Consequently, and in general, one can recommend one-step migration to the most recent production platform instead of making several steps of minor improvements. For GPON to TWDM-PON, all relevant systems are available now, meaning that this rule can be applied. It is not a typical situation to have so many technology generations available at the same time.

The migration from GPON to XG-PON requires the exchange of the OLT and ONU, because of the different speeds and because of the different wavelengths of the optical interfaces connecting the end-customers. This causes additional CAPEX. The backhaul interfaces towards the core network are Ethernet based with a capacity between 10 and 100 Gbps. Network upgrades of the aggregation and core network have to be performed due to the additional capacity (bandwidth demand) the new services will require. Upgrading the aggregation and core network is a permanent and regular business this study will not focus on. Migration from GPON to XG-PON is not recommended because further migration to XGS-PON would lead to a dead end, as described below (see also Section 6.1, migration 2).

The migration from XG-PON to XGS-PON is not recommended at all because of the identical wavelengths used. It would require long outage times or a parallel fibre plant, which nobody would deploy. The simple solution is a direct upgrade from XG-PON to TWDM-PON instead, or bypass XG-PON by directly migrating from GPON to XGS-PON.

The considerations regarding the migration effort for GPON to XGS-PON migration are comparable to those made for the GPON to XG-PON migration.

The most cost-saving migration scenario is the direct migration from GPON to TWDM-PON, because from today's point of view, this is the most powerful PON platform available. The direct migration saves any intermediate and additional CAPEX-/OPEX-intensive steps. This is not only true for the access network equipment, but also for the adaption of the OSS/BSS, the related processes and the parallel services complexity already described above (see introduction to Section 6).

Any provisioning of parallel NGA platforms causes additional CAPEX because the new platform only can perform efficiently if its capacity is fully used by all customers connected to the operator's network. Those customers still using the old platform are inefficient in this regard and cause additional OPEX due to two platforms operating in parallel. The customers should be actively migrated and the old system should be switched off, unless its capacity can be used for other services.

7 Conclusions

There is no economically feasible option for physical unbundling of the fibre access infrastructure of a PtMP topology unless in very densely populated areas and if the splitters are not cascaded. In the past, such topologies have been operated using GPON technology, which operates on one wavelength pair, with one wavelength for the downstream and one for the upstream communication direction. The splitter, a passive optical element located in the field, combines up to 64 end-customer access fibres onto one feeder fibre that is terminated at an OLT in the central office. The OLT controls the communication by allocating timeslots for each end-customer, just allowing one customer at a time to transmit its messages upstream and thus preventing signal distortion, because otherwise the optical signals of several end-customers could overlap and destroy each other on the feeder fibre. For downstream communication, the OLT addresses the ONU endpoints of the Optical Distribution Network (ODN), which is only allowed to receive and decode the messages dedicated to it. Due to the one feeder fibre, GPON communication uses a shared medium. The only option for supporting the Market 3a criterion of unbundling for such a GPON-based NGA network is a VULA.

The transmission technologies for PtMP fibre network topologies have evolved over time. XG-PON, XGS-PON and TWDM-PON options are available now or predicted to be available within one year. Their characteristics are summarised in Table 7-1.

Table 7-1: Overview of GPON technologies

Technology	No. of wavelengths (down/up)	Downstream bandwidth per wavelength [Gbit/s]	Upstream bandwidth per wavelength [Gbit/s]	Standardised
GPON	1/1	2.5	1.25	Y
XG-PON	1/1	10	2.5	Y
XGS-PON	1/1	10	10	Y
TWDM-PON	4/4 8/8	10	10	Y
PtP WDM overlay		10	10	not all

Source: WIK

With TWDM-PON, a wavelength plan has been defined and standardised to allow several wavelength pairs to operate in parallel. This allows wavelengths to be used in a futureproof manner, even if the incumbent operator does not use these wavelengths for its own business already. Wholesale seekers could couple their XG- or XGS-PON systems with WDM couplers into the ODN and operate them in parallel, and will thus be able to access all customers connected. Of course, some of the eight wavelength pairs should be allocated to the incumbent operator.

If the incumbent operator plans to deploy TWDM-PON today, the remaining wavelength pairs could be offered to wholesale seekers and the wholesale seekers may be coupled into the ODN via the TWDM-PON platform directly.

In any case, the number of wholesale seekers operating such networks in parallel is limited by the defined TWDM-PON wavelength plan. Future options including PtP wavelength might allow for unbundling in an individual manner (per customer), not limiting the number of competing operators in a structural manner. This may be a topic for future study when the standardisation is more mature.

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