Report for ComReg

Optical distribution network (ODN) sharing

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Contents

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1 Executive summary

The Commission for Communications Regulation (ComReg) appointed Analysys Mason to conduct a study in relation to the methods of, or options for, optical distribution network (ODN) sharing. ComReg seeks to understand the feasibility of the various options linked to ODN sharing and their impact on the promotion of competition and innovation within the broadband access market.

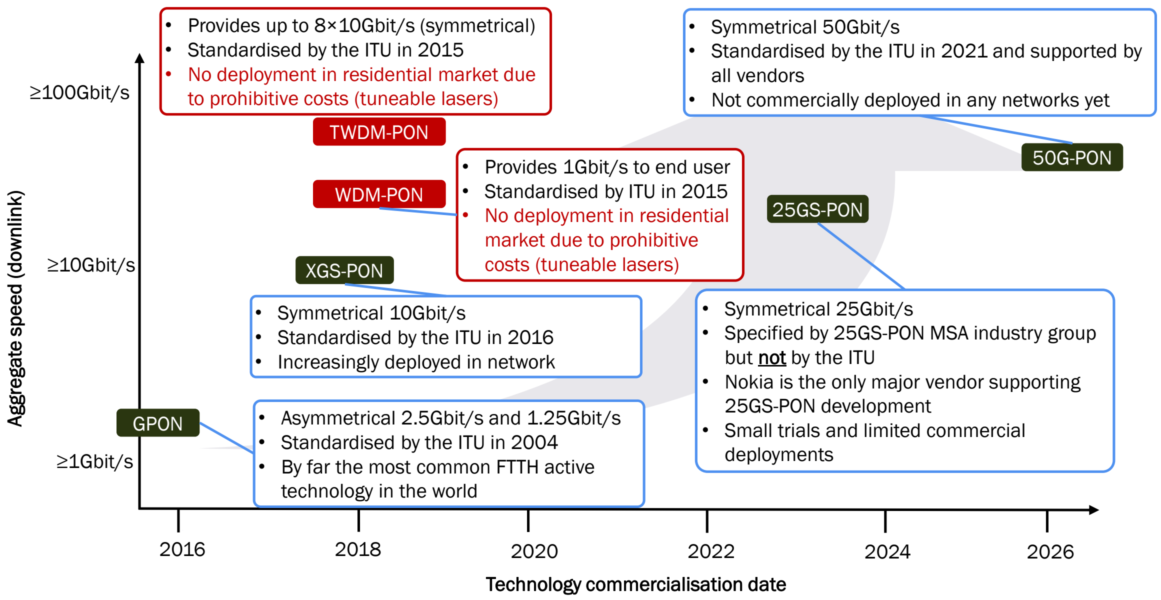
For this report, we define ODN sharing as the mechanisms which allow access seekers to take advantage of an existing third-party ODN (i.e. a wholesaler's access fibre network) to offer broadband services to other operators or to their own end users.

1.1 PON architecture and roadmap

PON technology roadmap

In order to cope with bandwidth growth, operators have had to replace their copper access networks with fibre access networks. Passive optical network (PON) has been the fibre access network architecture of choice and Gigabit PON (GPON) has been the most widely used active technology to address this requirement. The GPON technology family has been standardised by the International Telecommunication Union (ITU) since 2004. Figure 1.1 below provides a summary of the roadmap associated with GPON technology.

Figure 1.1: PON roadmap [Source: Analysys Mason, 2022]



As shown in Figure 1.1, we note that:

- **GPON**, which can offer 2.5Gbit/s in the downstream and 1.25Gbit/s in the upstream, is the most common technology deployed in PON networks outside China, Japan and South Korea.
- **XGS-PON**, which can offer 10Gbit/s[1] of symmetrical bandwidth, has gathered strong momentum, especially amongst alternative operators to differentiate themselves from incumbent operators, is forecast to overtake the number of GPON ports around 2023–2024.
- **TWDM[2]-PON**, which can offer up to eight XGS-PONs on the same ODN was a strong candidate for ODN sharing as it can support up to eight access seekers, each with their own virtual XGS-PON; however, TWDM-PON was never commercialised at scale due to the very high cost of the technology.
- **25GS-PON**, which can offer 25Gbit/s of symmetrical bandwidth, is not standardised by the ITU but instead specified by the MSA industry group[3] to fill the gap between XGS-PON and 50G-PON. 25GS-PON is currently positioned to address connectivity requirements of large enterprises and backhaul connectivity of 5G sites. Although there has been several trials which has demonstrated that 25G-PON can be deployed today in existing Nokia optical line terminals (OLTs), the number of commercial deployment remains very modest.
- **50G-PON**, which will be able to offer 50Gbit/s of symmetrical bandwidth and is being standardised by the ITU under the Higher Speed PON or HS-PON name, is gathering significant interest amongst operators globally but is expected to become commercially available for deployment for the mass market in the mid to late 2020s.

In addition to these active GPON technologies, the emergence of network functions virtualisation (NFV) and software-defined networking (SDN) has enabled the development of *network slicing*. This type of network architecture means that the access network can be logically partitioned into several virtual networks, each with their respective characteristics in terms of bandwidth, latency, priority, etc. and where each *slice* can be dedicated to an access seeker. NFV/SDN technology also allows new services with different characteristics to be created automatically without having to add any hardware in the network. Combining network slicing and automatic creation of new services is of great benefit to access seekers who could gain access to the wholesaler's network in such a way that they could directly create their own services without having to rely on the wholesaler's "static" products, further fostering innovation and competition. In order to realise this vision, the Broadband Forum[4] has defined the concept of fixed access network sharing (FANS) which specifies the different interfaces between wholesalers and access seekers.

PON technology co-existence

The GPON, XGS-PON and TWDM-PON/WDM PON standards are defined by the ITU to co-exist on the same physical ODN. This is achieved by allocating different wavelengths to different PON

1 The effective throughput to end users is only 8.5Gbit/s due to mandatory forward error correction (FEC) which consumes approximately 1.5Gbit/s of symmetrical bandwidth.

2 TWDM: time-wavelength division multiplexing.

3 Nokia is the only main PON active equipment vendor part of the multi-source agreement (MSA).

4 Non-profit industry consortium dedicated to developing broadband network specifications.

technologies so that they can be multiplexed together into the same fibre without interfering with each other. However, 50G-PON can only co-exist with **either** GPON **or** XGS-PON, which means that operators will have to either decommission GPON or XGS-PON when deploying 50G-PON.

In addition, the MSA industry-standards group has defined 25G-PON technology in such a way that it can also co-exist with GPON, XGS-PON, TWDM-PON/WDM PON on the same ODN.

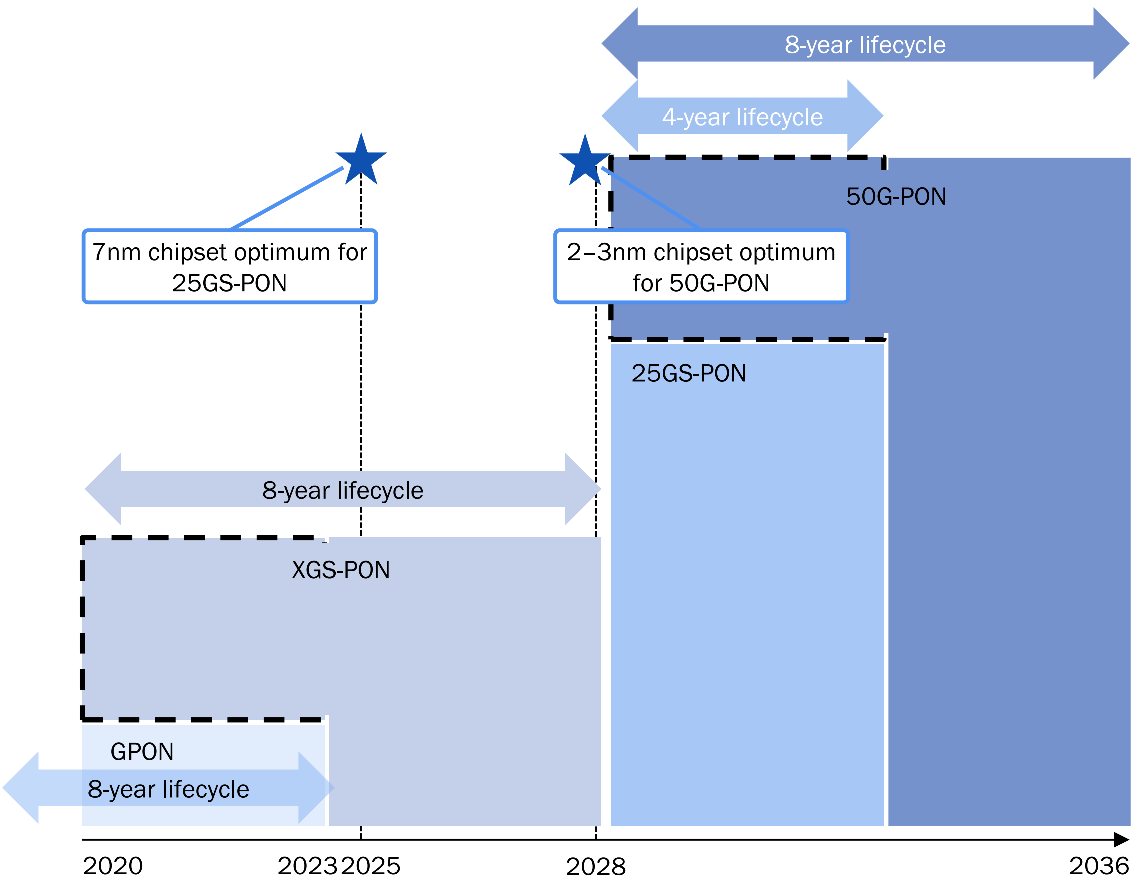
Factors affecting the adoption of PON technology

We have identified four key factors for the adoption of PON technology, which include:

- competitive environment
- bandwidth demand
- technology advancement and power consumption
- lifecycle and return on investment.

Some of these concepts are represented in Figure 1.2 to try and better understand the likely adoption of 25GS-PON and 50G-PON technologies by operators.

Figure 1.2: Lifecycle of PON technology vs. chipset [Source: Analysys Mason, 2022]



We believe that 25GS-PON will be a transition technology which may be needed to fulfil a set of niche applications (large enterprises, 5G backhaul, marketing of true 10Gbit/s broadband service), but will not be a large enough increment from XGS-PON to justify its deployment for the mass market given the expected short lifecycle and lack of standardisation from the ITU (which may mean low volumes and therefore high costs).

1.2 ODN sharing models

There are different ways to share on ODNs between operators depending on the network's open systems interconnection (OSI) layer considered:

- passive sharing (dark fibre)
- PON wavelength sharing
- wavelength overlay
- radio-frequency-over-glass (RFoG) ODN sharing
- Layer 2 active sharing (virtual unbundled access or VUA, and Bitstream)
- network slicing (SDN and NFV/FANs).

We describe each of these ODN sharing mechanisms and assess their technical feasibility and operational and commercial limitations in Figure 1.3.

Figure 1.3: Summary of ODN sharing mechanisms [Source: Analysys Mason, 2022]

ODN sharing mechanism	Description	Technical feasibility and other comments	Operational and commercial limitations
Passive sharing	• Dark fibre rented between hub site and the optical distribution point • Hub site consists of large cabinets where access seekers can locate their splitters and connect their network to the dark fibre to reach end user	• Technically feasible as implemented in rural France • Dark fibre may be purchased from wholesalers if available and appropriately located	• Expensive hub site-cabinet to locate the splitter – needs minimum adoption from access seeker to make it commercially viable • Issue associated with the fibre management of hub sites leading to potentially high fault rate • Ireland has opted for a different solution to resolve rural broadband digital divide (i.e. the National Broadband Plan)
PON wavelength sharing	• Access seeker to deploy active PON technology (e.g. 25GS-PON) on the wholesaler's ODN • Wholesaler makes co-existence element available to access seeker to connect its OLT to the ODN	• Technically feasible as different PON technologies are assigned different wavelengths	• Mechanism restricted to a single access seeker • Wholesaler prevented from deploying technology used by access seeker • Requirement for wholesaler to disable GPON or XGS-PON if access seeker deploys 50G-PON technology
Wavelength overlay	• Access seeker to deploy logical point-to-point (PtP) 10Gbit/s or 25Gbit/s wavelength over the wholesaler's ODN • Wholesaler makes co-existence element/WDM[5] multiplexer available to access seeker so it	• Technically feasible as PtP WDM technology has been available for two decades • Currently researched by ADTRAN[6] and should become available in early 2023	• Solution addresses requirements from large enterprise and 5G backhaul applications (not targeted at residential customers due to costs) – wavelength overlay is an alternative for vendors not supporting 25GS-PON – possibility to target residential market multi-dwelling units (MDUs) or grouping of small and

5 WDM: wavelength division multiplexing.

6 Global provider of networking and communications equipment.

ODN sharing mechanism	Description	Technical feasibility and other comments	Operational and commercial limitations
	can connect its WDM equipment to the ODN		medium businesses by installing a multiport switch as CPE[7] • Success of the wavelength overlay model will depend on how the wavelengths can be standardised
RFoG ODN sharing	• Cable operator access seeker to deploy RFoG technology over wholesaler's ODN • Wholesaler makes co-existence element/WDM multiplexer available to access seeker so it can connect its RFoG equipment to the ODN • Access seeker needs to deploy either of the following end-user equipment to multiplex/demultiplex RFoG signal: – micro-node with xPON output, or – PON ONT with RF output	• Technically feasible as RFoG wavelengths are different from xPON technology wavelengths	• Potential topology misalignment between cable network and the ODN in terms of equipment location • XGS-PON-based wholesale service has the potential to provide superior broadband services to DOCSIS[8] 3.1 (especially for the uplink and therefore cable operators would be better off purchasing VUA/Bitstream products from the wholesaler) • Replacement of RF[9] TV channels by IPTV[10] and OTT[11] content means that sharing ODN just for RF TV channels is not futureproof • Although DOCSIS 3.1 technology is still currently competitive, cable operators will eventually have to migrate to PON technology as DOCSIS does not provide a path to 50Gbit/s (as opposed to the PON roadmap)

7 Customer premises equipment.

8 Data over cable service interface specification.

9 Radio frequency.

10 Internet protocol television.

11 Over the top.

ODN sharing mechanism	Description	Technical feasibility and other comments	Operational and commercial limitations
Layer 2 active sharing (VUA and Bitstream)	• Wholesaler provides "Ethernet circuits" between a point of handover (PoH) and the optical network termination (ONT) • Access seeker interconnects with its own network at the PoH where relevant traffic is identified by means of virtual local area network (VLAN) tags	• VUA and Bitstream are proven wholesale products deployed worldwide	• VUA and Bitstream offer limited scope for innovation and competition due to the fixed nature of the wholesale products offered by the wholesaler as VUA and Bitstream are limited by: – xPON technology used (i.e. GPON vs. XGS-PON) – type of ONT used (i.e. 1Gbit/s ONTs vs. 2.5Gbit/s ONTs) – wholesale network design choices such as split ratio
Network slicing	• Logical partition on the wholesaler's network into several virtual networks (i.e. network slice), each with potentially different characteristics • Possibility for access seeker to access its own slice and create its own services	• Technically feasible as vendor claims to have a solution ready but still nascent technology for fixed networks • No commercial implementation to date in the context of ODN sharing • We expect this model to gather more pace commercially in the mid-to-late 2020s	• Wholesalers are not ready to allow access seekers to control part of their networks as it represents a significant paradigm shift compared to VUA/Bitstream wholesale products which are fully controlled by the wholesaler • APIs[12] and processes between access seekers and wholesaler need to be standardised for wider adoption, which is being facilitated by Broadband Forum FANS specifications, but more operator support is needed to drive adoption

12 Application programming interfaces.

2 Introduction

The Commission for Communications Regulation (ComReg) appointed Analysys Mason to conduct a study in relation to the methods of, or options for, optical distribution network (ODN) sharing. ComReg seeks to understand the feasibility of the various options linked to ODN sharing and their impact on the promotion of competition and innovation within the broadband access market.

This report details our findings in assessing the options for ODN sharing and is structured as follows:

- Section 3 provides an overview of passive optical network (PON) and point-to-point (PtP) technologies, and describes the options for coexistence of these technologies
- Section 4 provides an overview of radio-frequency-over-glass (RFoG) and the RFoG roadmap
- Section 5 describes the ODN sharing models
- Section 6 concludes the report by providing a summary of all ODN sharing models, assessing their technical feasibility and operational and commercial limitations.

In addition, this report contains three annexes:

- Annex A provides an introduction to wavelength division multiplexing (WDM)
- Annex B lists the contributors to this report
- Annex C provides a glossary of terms.

3 PON architecture and roadmap

With the growing demand for bandwidth and increasing cost of maintaining the copper access network, most telecoms operators in the world are in the process of upgrading their access network to fibre to the premises (FTTP). In order to achieve this, operators have two FTTP topology options:

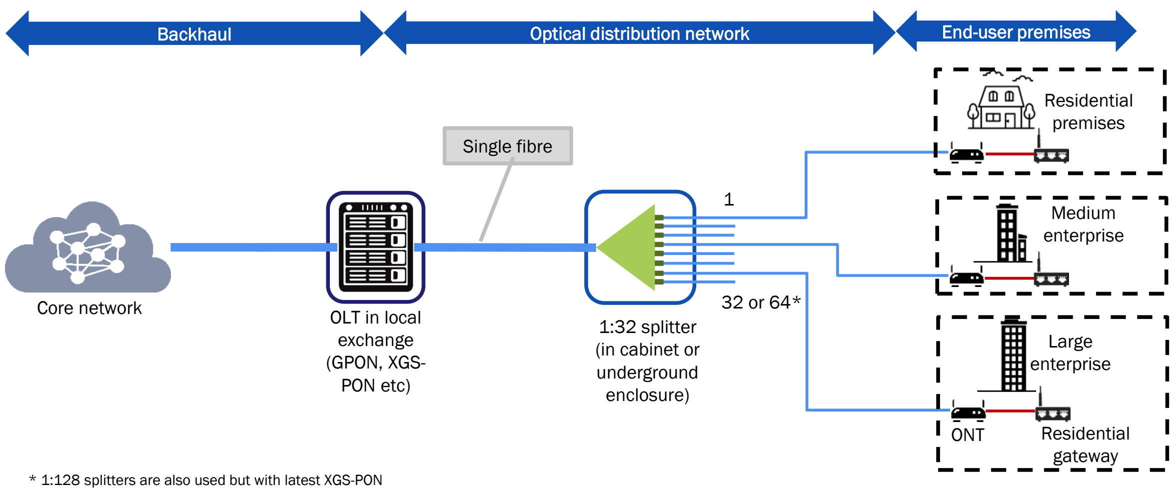
- PON topology
- PtP topology.

In this section, we look at these two FTTP topologies and their main components in turn. We then provide an overview of the technical roadmap associated with PON active equipment and describe selected deployment and trials to better understand the adoption of the latest PON technology standards (e.g. 25GS-PON and 50G-PON). We go on to explain how some of the PON technologies can co-exist together on the same ODN. Finally, we highlight the factors that operators consider when deploying the latest PON technology standards.

3.1 PON architecture

PON is a point-to-multipoint, FTTP-based architecture, in which un-powered (passive) optical splitters are used to enable a single optical fibre to serve a number of subscribers (typically up to 32 or 64). Components in the PON include the optical line terminal (OLT) at the infrastructure provider's local exchange and optical network terminals (ONTs) located with the end users. A residential gateway (RGW), which acts as a router and a Wi-Fi access point for the end-user end devices, is also present at the end-user premises and connected to the ONT. These components are illustrated in Figure 3.1.

Figure 3.1: PON network architecture [Source: Analysys Mason, 2022]



In a PON, the single fibre between the OLT and the passive splitter is shared by all customers connected to the PON, significantly reducing the requirements on the number of fibres in the network.

The active layer is defined as all electronic components in the network. There are two principal technology families for implementing the active layer for PON:

- **Ethernet PON (EPON)** is an IEEE/EFM[13] standard for using Ethernet in the last-mile standard (IEEE 802.3ah). EPON is applicable for data-centric networks, as well as full-service voice, data and video networks. EPON is less popular in Europe and in the USA than in China, Japan and South Korea where it dominates. Since this report is designed to inform ComReg in Ireland, **we do not discuss EPON in the rest of this report but concentrate on the GPON technology family**.
- **Gigabit PON (GPON)** standardisation is supported by the International Telecommunications Union (ITU) and the Full-Service Access Network (FSAN[14]) industry association. GPON is, by far, the most popular PON technology in the USA and in Europe. With the increase in bandwidth demand, successive technologies have been standardised by the ITU including GPON, NG-PON1 and NG-PON2 as described in Section 3.3.

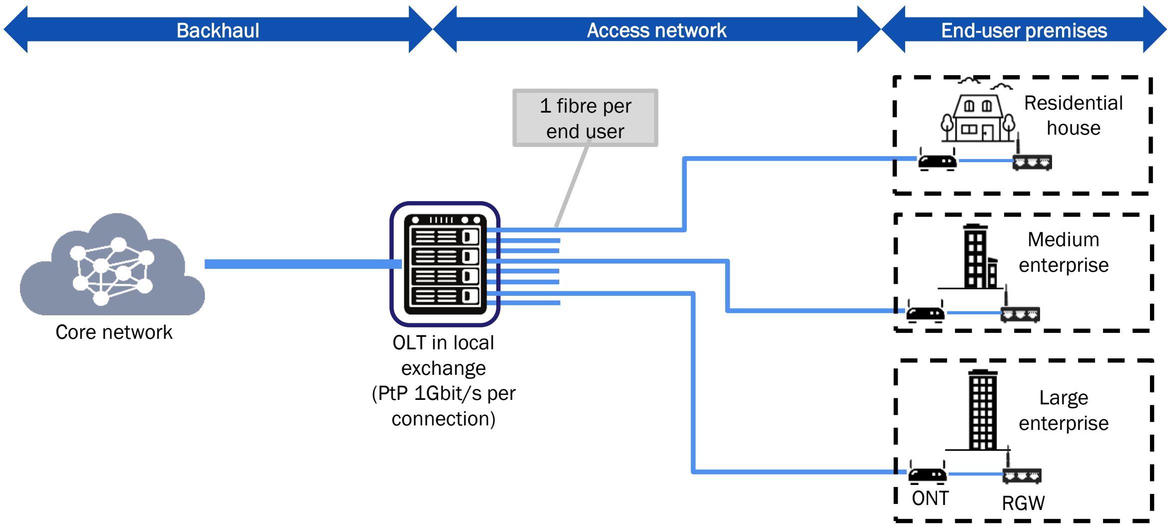
3.2 PtP architecture

PtP architecture is based on Ethernet technology and is therefore standardised by the IEEE standardisation body. PtP access networks are implemented by means of a dedicated fibre (with dedicated capacity) between the OLT site (located in a local exchange or in a cabin) and each individual end-user premises. This is illustrated in Figure 3.2.

13 IEEE/EFM: Institute of Electrical and Electronics Engineers/Ethernet in the first mile.

14 FSAN is not a standards development organisation (SDO) in itself but brings a technical contribution to the standards. It is composed of telecoms operators, equipment manufacturers, chip vendors and device manufacturers including China Telecom, China Unicom and other major global telecoms operators, and Huawei, ZTE, Fibrehome and other major global equipment manufacturers, as well as Mitsubishi, Macom, Marvell, Finisar, Hisense, Broadcom and other major device and chip manufacturers.

Figure 3.2: PtP architecture [Source: Analysys Mason, 2022]



PtP network architecture was quite popular with early adopters of FTTP as, at that time, PON technology was not mature enough. However, given the subsequent success of GPON technology, some early adopters of PtP have now reverted to GPON. This is achieved by simply replacing the PtP OLT/ONT with a GPON OLT/ONT and placing a splitter in the local exchange (i.e. OLT location), therefore preserving the deployment of physical PtP infrastructure.

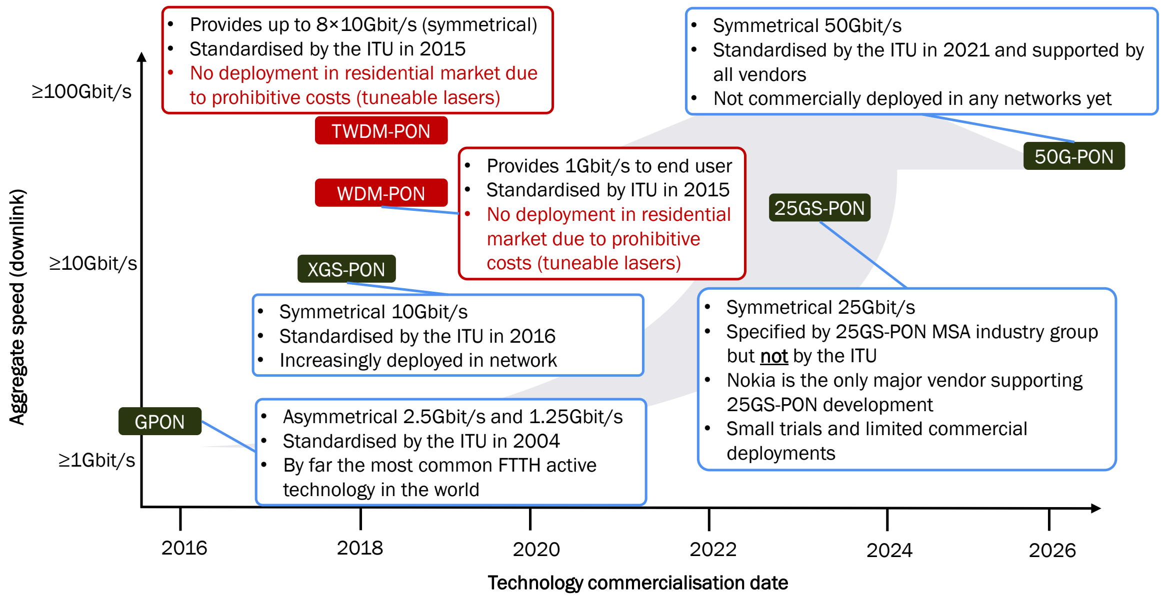
3.3 PON roadmap

To guide the development of existing and future PON technology standards, FSAN set out a PON technology roadmap in December 2016 which defines five main GPON/NGPON technology families:

- GPON
- next-generation PON 1 (NG-PON1)
- next-generation PON 2 (NG-PON2)
- XG(S)-PON+ and NG-PON2+
- future optical access system (FOAS).

We summarise the main characteristics of the PON roadmap in Figure 3.3 and describe in more detail each of these technologies below.

Figure 3.3: PON roadmap [Source: Analysys Mason, 2022]



3.3.1 GPON

GPON is the most common technology deployed in PONs outside China, Japan and South Korea. GPON was standardised in 2004 by the ITU-T (G.984 standards) and can provide 2.5Gbit/s of bandwidth in the downstream direction and 1.25Gbit/s of bandwidth in the upstream direction. As a PON-based technology, the downstream and upstream bandwidths are both shared between all users connected to the PON (usually between 32 or 64 end users depending on operator or target market).

3.3.2 NG-PON1

NG-PON1 standards essentially include two different NG-PON technologies: 10Gbit/s PON (XG-PON) and 10Gbit/s symmetrical PON (XGS-PON).

XG-PON XG-PON was standardised (ITU G.987) in 2009 and can provide an asymmetrical bandwidth of 10Gbit/s downstream and 2.5Gbit/s upstream. XG-PON is essentially a higher-bandwidth version of GPON. It has the same capabilities as GPON and can co-exist on the same fibre with GPON. XG-PON has been trialled and commercially deployed by a small number of operators prior to 2017 (e.g. KDDI, Singtel and Etisalat) but is no longer deployed as it has been superseded by XGS-PON.

XGS-PON Recognising the limitations of the asymmetrical profile of XG-PON due to the increasing demand for upstream bandwidth created by social media and gaming, XGS-PON was standardised under ITU G.9807.1 in 2016. XGS-PON provides 10Gbit/s of bandwidth for both the upstream and the downstream, but only provides approximately 8.5Gbit/s of useful throughput at Layer 2 to end users. This is because XGS-PON technology includes mandatory forward error correction (FEC)[15] which occupies approximately 1.5Gbit/s (i.e. bandwidth that cannot be accessed by end users). XGS-PON can also co-exist with GPON on the same PON, but cannot co-exist with XG-PON. XGS-PON has been commercially deployed by a large number of operators (e.g. Siro, NBI and eir in Ireland; Trooli, Toob and Wildanet in the UK; Ooredoo Qatar, China Telecom; Salt in Switzerland; AT&T; Telefónica Spain just to name a few) and has gathered some momentum amongst operators.

3.3.3 NG PON2

NG-PON2 standards essentially include two different NG-PON technologies: time-wavelength division multiplexing PON (TWDM-PON) and wavelength division multiplexing PON (WDM-PON).

TWDM-PON

TWDM-PON[16] was standardised as part of the NG-PON2 standards under ITU G.989 in 2015.

Characterised by flexible bit-rate wavelengths,[17] TWDM-PON can provide the equivalent of up to eight[18] XGS-PON[19] overlay systems within a single PON. Each XGS-PON uses different wavelengths to co-exist in the same ODN. To get the full benefits of wavelength mobility,[20] tuneable lasers[21] are required.

TWDM-PON was a technology that attracted a lot of interest from regulators in Europe as it was considered to be an enabler for full broadband service unbundling where up to eight different retail service providers could effectively operate a separate XGS-PON over a common ODN.[22,23]

15 FEC consists in including additional redundancy information in the signal so that if some of the data gets corrupted during transmission, the original data can be reconstructed at the receiver (i.e. removing the need to retransmit the data).

16 TWDM-PON is part of the NG-PON 2 family.

17 TWDM-PON wavelength can either be 2.5Gbit/s or 10Gbit/s.

18 G.989.2 fully standardises TWDM PON for 4 wavelengths but the full standardisation of 8 wavelength systems is for further work. However, G.989.2 already allocates up to 8 wavelengths in each direction for TWDM-PON.

19 Or a mix of XG-PON and XGS-PON.

20 Wavelength mobility refers to the ability of dynamically turning on or off particular wavelengths, switch across wavelengths, or logically bonding wavelengths together.

21 Tuneable laser refers to the fact that the wavelength emitted by the laser can be tuned (i.e. changed).

22 https://berec.europa.eu/eng/document_register/subject_matter/berec/reports/7297-berec-report-on-the-new-forms-of-sharing-passive-optical-networks-based-on-wavelength-division-multiplexing

23 https://www.comreg.ie/?dlm_download=gpon-twdm-gpon-context-wholesale-local-access-market

However, TWDM-PON technology was never deployed in volumes (only deployed in the USA by AT&T and Altice on relatively small footprints). The main issue associated with TWDM-PON is that it requires ONTs with tuneable lasers which are too expensive for the mass residential market (i.e. a TWDM-capable ONT is priced at ~USD1500 compared to EUR25 and USD70 for GPON and XGS-PON ONTs respectively today). We do not expect TWDM-PON to be deployed as a new technology by any operators worldwide, which favour instead cheaper and fixed wavelength technologies such as XGS-PON.

WDM-PON

WDM-PON was also standardised as part of the NG-PON2 standards in 2015. WDM-PON functions by allocating a dedicated wavelength to every end user on the PON, effectively providing them with a logical PtP connection. WDM-PON currently typically provides a dedicated 1Gbit/s of symmetrical bandwidth to each connected end user.

However, similarly to TWDM-PON, WDM-PON requires tuneable lasers, making it expensive to deploy in mass residential markets, hence its lack of adoption to date as a technology for the residential market and very low adoption in the business market.

3.3.4 NG-PON2+

FTTP operators worldwide are increasingly upgrading their networks from GPON to XGS-PON. The number of XGS-PON ports worldwide is expected to overtake the number of GPON ports around 2023–2024. However, the desire to extract as much capacity as possible from fibre networks means that there is significant interest in PON technologies that offer capacity beyond 10Gbit/s XGS-PON, such as 25GS-PON and 50G-PON collectively known as NG-PON2+.

25GS-PON

Since NG-PON2 is proving too costly to deploy, 25GS-PON – which provides 25Gbit/s of symmetrical bandwidth – is being actively pursued by the 25GS-PON multi-source agreement (MSA) industry-standards group. Key operator members of this group include nbn, AT&T, Chunghwa, Chorus, INEA and Proximus, and a key equipment vendor is Nokia. The stated goal of this group was "to promote and accelerate the development of 25 Gigabit Symmetric Passive Optical Network technology[24]" because the ITU had not reached a consensus to standardise any 25Gbit/s PON and decided to focus instead on 50G-PON (discussed below). The main reason for the ITU not to endorse 25GS-PON was that it felt that an increment of 2.5 times was not sufficient compared to

24 25GS-PON Group, 25 Gigabit Symmetric Passive Optical Network Specifications, October 2020.

XGS-PON and a fivefold increase (with 50G-PON) meant that operators could have a better return on investment on the full lifecycle of the technology.

Nokia's 25Gbit/s technology is powered by its own Quillion chipsets, which are now deployed in new GPON and XGS-PON 'combo cards',[25] thereby making ~80[26] recent Nokia deployments 25GS-PON-ready worldwide.

Today, 25GS-PON technology is positioned as an interim toolkit to address two main use cases:

- large business connectivity
- 5G backhaul and fronthaul.

Demand for high-bandwidth services from large enterprises (and even campus environments) that have been traditionally served by PtP Ethernet services is on the rise and operators have acknowledged that they cannot wait for 50G-PON technology to be fully standardised and tested. 25GS-PON is seen as a technology to bridge the gap between XGS-PON and 50G-PON, demonstrated by the number of trials that have been publicly announced thus far. This will allow enterprises to access true 10Gbit/s symmetrical speeds and upwards, which XGS-PON does not provide.[27] There is a case for 25GS-PON in 5G backhaul networks, particularly around small-cell connectivity as interest in the development of smart cities is on the rise (for example 5G transport networks).[28]

For operators using Nokia PON equipment, it is relatively easy to introduce 25GS-PON technology into their network as the same OLT used in the XGS-PON can be used for 25GS-PON, although 25GS-PON OLT cards can currently only accommodate 8 ports compared to 16 ports for GPON/XGS-PON combo cards. A combo card is an OLT card which allows the simultaneous transmission of two PON technologies through the same port without the need for any external co-existence element.

► *25GS-PON trials and commercial deployment*

A number of operators have officially announced that they are trialling 25GS-PON technology. We provide a few examples below:

Proximus trial, Antwerp harbour, Belgium, May 2021	Proximus became one of the first operators to demonstrate the capabilities of 25GS-PON technology with Nokia when it trialled the technology to connect

25 A combo card is a port which can provide both GPON and XGS-PON at the same time over the same PON.

26 According to Nokia.

27 As mentioned previously, XGS-PON can only provide a maximum of 8.5Gbit/s of useful bandwidth to end users at layer 2 due to mandatory FEC.

28 https://www.delloro.com/timing-and-operator-control-keys-for-25g-pon/

the Antwerp harbour in 2021 and achieved a speed of 21Gbit/s. Proximus expects the first commercial use case to be in industry-based enterprise.[29,30]

Openreach trial in Ipswich, UK, July 2021

Openreach announced its trial of Nokia's 25GS-PON technology in July 2021 with plans to launch a field trial on high-bandwidth applications later in the year.[31,32] Updates on the launch or completion of the field trial have yet to be made publicly available.

TIM trial in Turin, Italy, September 2021

TIM partnered with Nokia to test the use of already deployed OLTs to deliver 25GS-PON at its laboratory in Turin. The operator tested the co-existence of GPON, XGS PON and 25GS-PON with an aim to offer high-bandwidth connectivity for industrial districts, businesses and government entities.[33]

Bell Canada trial in Montreal, Canada, November 2021

In November 2021, Bell Canada announced that it had successfully trialled PON technologies in Montreal, including GPON, XGS PON and 25GS-PON, using Nokia equipment on the same fibre.[34] The aim of the trial was to prove that the PON technologies can work together to provide high-bandwidth capacity for enterprise services and 5G transport.[35]

Türk Telekom trial in Turkey, November 2021

Türk Telekom announced the successful trial of 25GS-PON using Nokia equipment in November 2021. The operator is focused on delivering services to support smart cities, office and home services with the high-capacity technology. Türk Telekom successfully achieved speeds of 20Gbit/s in the downstream and 9.1Gbit/s in the upstream with the aim to deliver 16K TV and 3D 360-degree videos and augmented reality/virtual reality (AR/VR) application.[36]

CityFibre trial, Glasgow, Scotland, December 2021

CityFibre teamed up with Nokia in Glasgow (Scotland) to conduct the UK's first successful demonstration of a trial that used their full-fibre 25GS-PON kit to fuel backhaul capacity for a 5G mobile (mobile broadband) network,

29 https://www.proximus.com/fr/news/2021/20210526-proximus-and-nokia-unveil-world-premiere.html;pxcfrontend=w3aoQ6fLruoo0mG5D6ycxVfrT_TxJnuHWMjFxj2P.pxcp_frontend_22

30 https://www.fiercetelecom.com/telecom/nokia-proximus-claim-first-25g-fibre-network

31 https://www.fiercetelecom.com/tech/bt-s-openreach-tests-nokia-s-25g-pon-fibre-technology

32 https://www.nokia.com/about-us/news/releases/2021/07/16/openreach-and-nokia-test-25g-pon-fibre-broadband-technology/

33 https://www.gruppotim.it/en/press-archive/corporate/2021/PR-TIM-FTTH-25GBPS-14-settembre-2021-EN.html

34 https://www.telecompetitor.com/first-25g-pon-trial-comes-to-n-america-courtesy-of-bell-canada-nokia/

35 https://www.nokia.com/about-us/news/releases/2021/11/16/nokia-and-bell-canada-test-25g-pon-fibre-broadband-technology/

36 https://www.nokia.com/about-us/news/releases/2021/11/30/nokia-and-turk-telekom-successfully-test-25g-pon-technology-in-turkey/

which was used to demonstrate a holographic call between buildings, teleoperation of a robotic arm and 8K video streaming.[37]

Frontier trial in the USA, December 2021	Frontier became the first operator in the USA to announce its test of 25GS-PON using Nokia's technology in December 2021 soon after connecting its XGS-PON network to 100 000 premises. The operator announced plans to deploy its commercial 25GS-PON network in H2 2022 and has a target of 10 million premises on its fibre network by 2025.[38]
Hrvatski Telekom trial in Rijeka, Croatia, March 2022	In March 2022, Hrvatski Telekom (part of the Deutsche Telekom Group) became the first operator to announce the successful trial of Nokia's 25GS-PON technology in Croatia. The trial was conducted in a lab in Rijeka to demonstrate the compatibility with XGS-PON, PtP Ethernet and GPON to increase capacity on its existing network.[39]
Chorus trial in Auckland, New Zealand, May 2022	Chorus and Nokia announced the successful trial of the 25GS-PON technology in Auckland, achieving download speeds of 21.4Gbit/s over the same fibre marketed as 'Hyperfibre' (GPON, XGS PON and 25GS-PON). Chorus aims to provide high-speed services to wholesale service providers and then to business and residential end users. For business users in particular, Chorus is targeting services that provide low-latency cloud connectivity and industrial metaverse applications.[40]
AT&T trial in the USA, June 2022	Following the signing of the 25GS-PON MSA in March, AT&T (member of the 25GS-PON industry group) launched a trial of the 25G technology. Initially, the operator tested the technologies downstream capabilities with asymmetrical 10Gbit/s upstream speed and has since moved on to testing the symmetrical capabilities. During the trial, the operator leveraged the existing fibre deployment using the existing OLTs with Quillion chipsets deployed in its XGS PON network and new photonics.[41]

Although a number of successful trials have been announced, commercial deployment of 25GS-PON technology remains modest and in very small footprints as shown below:

Hotwire commercial deployment in the	Hotwire became one of the first operators in the world to deploy 25GS-PON in its network. The operator is a well-known disruptor in the American market, and with this deployment aims to deliver symmetrical speeds of

[37] https://www.ispreview.co.uk/index.php/2021/12/nokia-demo-first-uk-trial-of-25g-pon-for-5g-backhaul-with-cityfibre.html

[38] https://www.fiercetelecom.com/broadband/frontier-teams-nokia-25g-pon-trials

[39] https://www.computerweekly.com/news/252514503/Nokia-and-Hrvatski-Telekom-conduct-first-25G-PON-fibre-broadband-trial-in-Croatia

[40] https://company.chorus.co.nz/chorus-and-nokia-demonstrate-future-fibre-their-first-trial-25g-pon-broadband

[41] https://www.fiercetelecom.com/broadband/att-exec-says-mainstream-25g-rollouts-likely-2024-story

USA, December 2021	10Gbit/s and more to customers, starting with multi-dwelling units (MDUs).[42]
EPB commercial deployment in a conference centre, USA, July 2022	EPB has launched the USA's first community-wide 25Gbit/s internet service to be available to all residential and commercial customers over a 100% fibre-optic network with symmetrical upload and download speeds. Through a partnership with Hamilton County and the City of Chattanooga, the Chattanooga-Hamilton County Convention Center is EPB's first 25Gbit/s customer, making it the first convention centre worldwide to offer such fast speeds over a broadband network. With this technology, the convention centre will be able to simultaneously provide high-bandwidth connectivity to thousands of smart devices to draw business conferences, e-gaming competitions, live streaming events and more.

During our interviews with Nokia, it has announced that it currently has three commercial contracts in relation to 25GS-PON including the above cases. Based on the above evidence, it seems that 25GS-PON will be deployed for niche applications (e.g. large enterprise connectivity, 5G backhaul and providing premium broadband to affluent residential areas) and not for the residential mass market (at least in the short-to-medium term).

50G-PON

Mainly due to the fact that it is being standardised by the ITU, there is considerable interest in 50G-PON deployments among the global operator community. For example, the Lianyungang branch of China Mobile completed a successful test of the technology on its live network[43] in 2022. This is significant because the scale of the FTTP roll-out means that 50G-PON deployment in a country as large as China can generate very substantial economies of scale, which may help to reduce costs for operators in other parts of the world. Operator interest in 50G-PON is not confined to China; major European operators such as Swisscom and Telefónica are investigating its potential. Telefónica has recently stated that it envisages deploying 50G-PON in the medium term following the initial step of deploying XGS-PON. Telefónica's interest in the technology is particularly important due to the operator's strong presence across Latin America and its extensive ultra-broadband footprint (154.7 million premises at the end of H1 2021).

Operators' support of 50G-PON worldwide also reflects the standardisation of the technology; this process started in 2018. The ITU officially published the first version of the 50G-PON standard in September 2021 (Standard ITU G.9804) for single-wavelength systems.[44]

42 https://hotwirecommunications.com/25gpon/

43 50G-PON offers a solution for operators that are looking to move beyond XGS-PON, Analysys Mason, December 2021.

44 Multiple-wavelength systems remain under study.

The complexity of 50G-PON systems is a little greater than that of earlier PON generations, but the significant deployment volumes for new PON technologies lead to substantial cost reductions. This is demonstrated by how the costs for XGS-PON have fallen over time. Such a scenario is also likely for 50G-PON. 50G-PON systems can also make use of digital signal processing (DSP), which means that they will be able to use lower-cost 25G optical components. The cost of DSP can be amortised across growing deployment volumes and will be reduced over time as described in Moore's law (see Section 3.5.3 for more details). Experimental 50G-PON/XGS-PON combo cards already exist and have been tested in Huawei laboratories; these have a density of 8 ports per card.

Although research suggests 50G-PON network deployment at scale will likely begin in the late 2020s, Huawei suggests commercial deployments may begin as early as 2024. A key factor will be the commercial availability of advanced digital signal processor (DSP).[45] Like 25GS-PON, early 50G-PON deployments will likely target niche markets such as large enterprises (industrial), 5G backhaul (small cells) and affluent residential areas where demand for 2Gbit/s products and higher is emerging.[46] However, as technology adoption increases and cost erodes, we expect 50G-PON to eventually target mass residential markets in the mid-to-late 2020s.

► *50G-PON trials and commercial deployment*

Two trials of 50G-PON have been publicly announced thus far:

Swisscom trial in Switzerland, October 2020	Swisscom first announced its trial of 50G-PON technology in 2020 using a prototype line card which at the time had not confirmed its supplier. Markus Reber, the Executive Vice President of Networks, identified the initial target market as business customers who would require access to high-bandwidth products that are flexible to meet their requirements, enabled through network virtualisation.[47] In 2022, Swisscom announced it had successfully tested 50G-PON in a live network and aims to deploy the technology in 2025.[48] Huawei has since confirmed it is the supplier of the technology.[46,49]
China Mobile trial in China, April 2021	Huawei reportedly confirmed China Mobile completed a successful trial in a lab in April 2021, achieving 41Gbit/s download and 16Gbit/s upload speeds and low latency. In 2022, at the Optical Fibre Communication Conference (OFC 2022), a field trial using 50 TDM-PON technology for 5G backhaul (small cell) was conducted. The operator reportedly aims to conduct further

45 https://www.strategyanalytics.com/strategy-analytics/blogs/service-providers/networks-and-service-platforms/networks-service-platforms/2022/03/16/50g-pon-advances-toward-commercialization

46 According to Huawei.

47 https://www.lightwaveonline.com/fttx/pon-systems/article/14185094/swisscom-trials-50g-pon

48 https://www.lightwaveonline.com/fttx/pon-systems/article/14279867/swisscom-tests-50g-pon-in-live-network

49 https://www.commsupdate.com/articles/2022/07/12/swisscom-completes-50g-pon-trial-on-live-network/

field trials in 2023 and begin commercial deployment of its 50G-PON network in 2025.[50]

In addition to Swisscom's and Telefónica's interest in 50G-PON, a few other operators have announced their preference for 50G-PON over 25GS-PON, including France's Orange and Turkey's Turkcell which plans to deploy 50G-PON in 2024.[50] Other than Huawei, a few vendors have announced successful trials of their 50G-PON prototype technologies:

FibreHome trial in Baoding, China, December 2021	FibreHome, a major network and equipment provider in China announced it had completed a pilot project of the 50G-PON technology to verify the high bandwidth, low latency and potential new service (for example VR/AR, 8K UHD video and desktop cloud) capabilities of the technology. FibreHome's AN6000 OLT was used in the pilot project to verify the performance of the technology, reaching download speeds of 40.3Gbit/s and upload speeds of 12.3Gbit/s, as well as the technology's ability to support 5G base stations, demonstrating the reduction in jitter.[51]
ZTE release of prototype Barcelona, Spain, March 2022	At the Mobile World Congress 2022, ZTE launched its precise 50G-PON prototype which supports up to 50Gbit/s per wavelength through timeslot-based pipes. The timeslot-based technology allows for the parent slot to control and distribute bandwidth within the network, providing bandwidth of up to 10Gbit/s, reduced latency to 200 microseconds and reduced jitter to nanoseconds.[52]

3.3.5 Impact of network functions virtualisation (NFV) and software-defined networking (SDN) on PON networks

In common with other telecoms network elements, it is expected that PONs will eventually be virtualised and deployed using cloud-native technologies. This will reduce the amount of hardware required, thus significantly reducing power, cooling and maintenance costs. Also, cloud-native technology will enable the use of containerised microservices that are not dependent on purpose-built hardware, but run in software containers deployed on off-the-shelf servers (which may or may not actually be located in the cloud). They are easy to test, deploy and upgrade individually, without having to disrupt the whole system.

50 https://blog.huawei.com/2022/07/08/50g-pon-clear-winner-25g/

51 http://www.cww.net.cn/article?from=timeline&id=495533&isappinstalled=0

52 https://www.zte.com.cn/global/about/news/20220302e3.html

NFV and SDN concepts applied to access networks

The first step into virtualisation is to disaggregate control functions from the physical layer. This is achieved by creating an abstraction layer of the system that sits in-between the hardware and the SDN controller.

Then, a central control function, i.e. an SDN controller, can be implemented to control all PONs, which will enable new services to be provided on the PON. Let us illustrate this flexibility with the example of "instantaneous download". Some video games are quite large to download (e.g. hundreds of gibabytes). If the FTTP network was virtualised and equipped with an SDN controller, it would be possible to significantly increase the bandwidth provided to the end user so that the game can be downloaded faster (e.g. in 5 minutes instead of 25 minutes). This feature would improve the gamer's quality of experience of the service. In return, the broadband service provider could either charge the end user an additional fee for this service or directly charge the game editor for an incremental fee.

Virtualising the network will also enable the creation of virtual network functions (VNF) without the requirement for new hardware. For example, if an FTTP area was under cyber attack, it would be possible to automatically create a virtualised firewall on the OLT to protect the area from the attack.

Using SDN and NFV, it is possible to create several discrete "network slices" over the existing FTTP network in a fully programmable way. Each slice can be programmed to have different technical characteristics such as latency, throughput or packet prioritisation to feel and look the same as a physical network. Virtual network slices can be created for specific applications or for specific operators (or a combination of both).

Commercial availability of software-defined access networks (SDANs)

An SDN controller for FTTP access networks is commercially available and is in the early stages of adoption; for example, Nokia has 70 commercial SDN controller contracts with operators around the world.[53] Advantages of virtualising some of the functions of the OLT and using an SDN controller include:

53 According to Nokia.

Figure 3.4: Benefits of SDANs [Source: Nokia, 2022]

Disaggregation	Abstraction	Automation
▪ Hardware and software layers can be scaled separately	▪ Operations are abstracted from implementation	▪ Networks are controlled by software functionality
▪ New services and features can be introduced easily	▪ Provisioning and troubleshooting processes are simplified	▪ Network routines can be automated and adapted flexibly
▪ IT-like approach with DevOps and micro-services that yield shorter innovation cycles	▪ Portability is maximised for future network evolutions	▪ Opex is reduced via closed-loop automation, health analysis and zero-touch operations

However, SDN controllers are currently limited to be used by a single operator. For example, traditional incumbents are exploring the technology for their own benefits mentioned above and not yet with a view to enabling access seekers to control their networks and create their own services.

Fixed access network sharing (FANS)

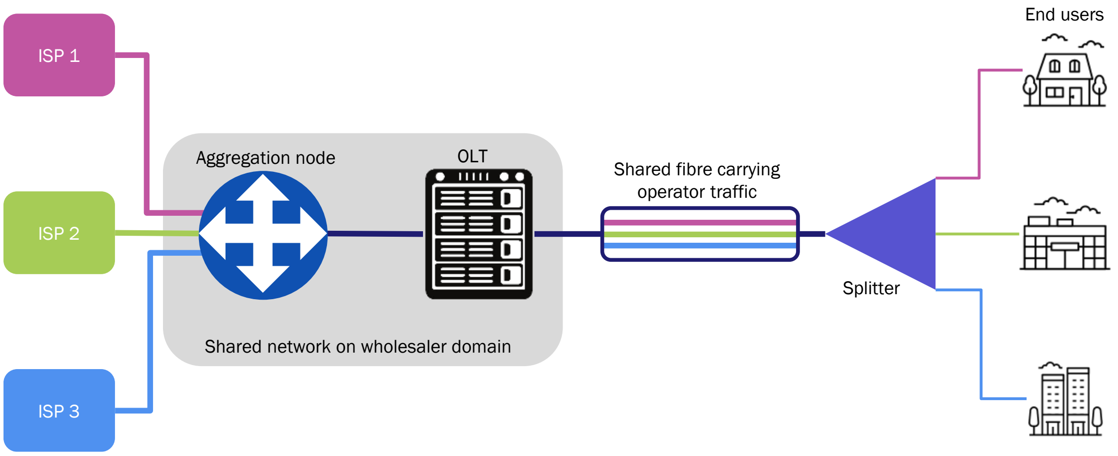
The ultimate vision in SDAN is that new services with different characteristics can be created and torn down automatically without having to add any hardware in the network. Extending this idea to ODN sharing, it would be of great benefit if access seekers could gain access to the wholesaler's network in such a way that they could directly create their own services without having to rely on the wholesaler's "static" products, further fostering innovation and competition. In order to realise this vision, the Broadband Forum has defined the concept of FANS.

FANS is a highly enhanced form of virtual unbundling on fixed access networks that allows the costs of deploying an ultrafast broadband network to be shared by the infrastructure provider (i.e. wholesaler) and virtual network operators (i.e. access seekers). FANS automates and harmonises data, control and management interfaces between the wholesaler and the access seeker. Importantly, FANS standardises interfaces between the wholesaler and the access seeker.[54]

FANS logically partitions and isolates network resources to form different "slices" for different access seekers. This is achieved through SDN and NFV. Each network slice becomes an independent virtual network which can be operated, managed and controlled by the access seekers themselves to meet their own operational requirements, as shown in Figure 3.5.

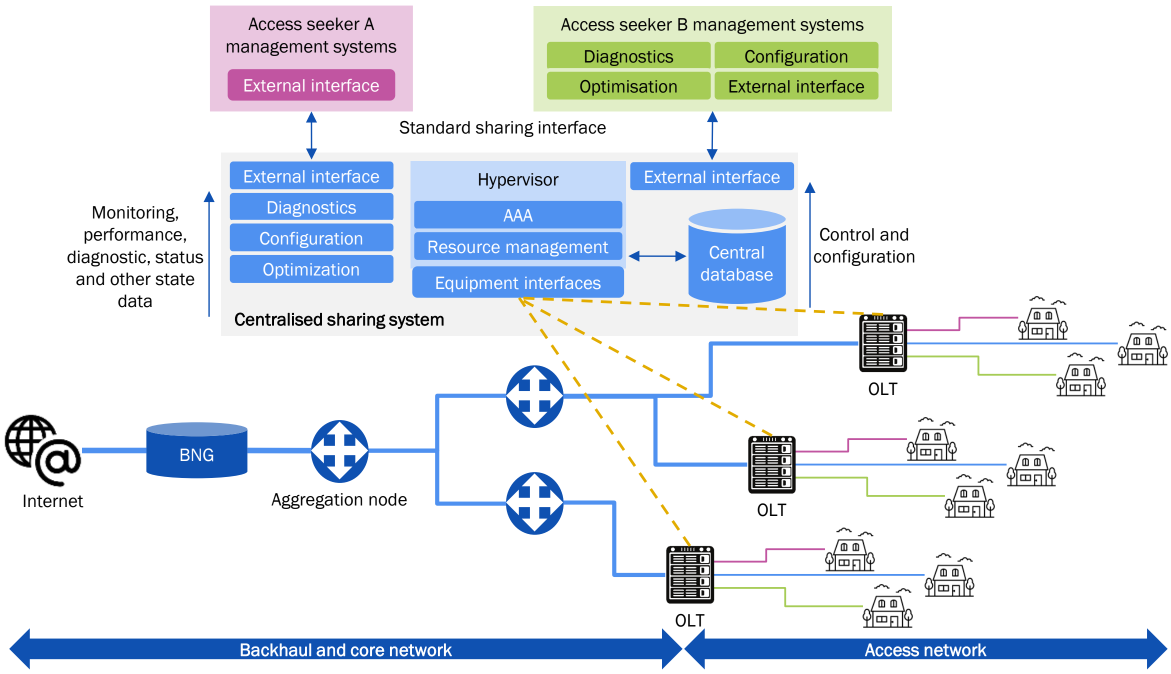
54 https://www.broadband-forum.org/marketing/download/MR-453.pdf

Figure 3.5: Example of FANS [Source: Analysys Mason, 2022]



The specification of the shared interfaces between the wholesaler and the access seekers is provided in Figure 3.6.

Figure 3.6: FANS centralised management system interfaces [Source: Broadband forum, 2022]



As shown in Figure 3.6, FANS is made up of several components. The centralised management system is where the interfaces sit, controlling functions such as authentication, authorisation and accounting (AAA), and controls specific operations (configuration, diagnostics, etc.). Resources such as computing infrastructure are then managed by the wholesaler, controlling and assigning access to the ISPs and preventing the sharing of confidential data across ISPs. Traffic is then transferred on the wholesaler's backhaul network or onto the access seeker's own backhaul. In a virtualised network using FANS, a multi-protocol label switching (MPLS) technique can be used to segregate the data onto the backhaul network(s).

Several use cases emerge with the implementation of FANS on the fibre network:[55]

- **monitoring and optimisation of network performance** – real-time access to monitoring data to manage faults, change or improve performance and increase capacity
- **fault correlation** – correlation of fault data across multiple lines
- **configuration** – virtual configuration of the network to provide differentiated products, QoS, speed and network stability
- **segmentation** – allows for network segmentation for various functions, for example differing operational teams.
- **service innovation** – allows for access seekers to offer differentiated services designed to meet end-user profiles.

The service innovation use case is particularly relevant in the context of ODN sharing.

3.4 Co-existence of xPON technologies

3.4.1 Co-existence of GPON, NG-PON1 and NG-PON2

The GPON, NG-PON1 and NG-PON2 standards are defined to co-exist on the same physical PON. This is achieved by allocating different wavelengths to different PON technologies so that they can be multiplexed together into the same fibre without interfering with each other. The technology is known as WDM. The wavelength division multiplexer/demultiplexer which allows all wavelengths to be multiplexed/demultiplexed onto the same fibre is known as the co-existence element (CE).

The standardised spectrum[56] used by each (N)G-PON technology is illustrated in Figure 3.7 and the multiplexing of GPON, NG-PON1 and NG-PON2 is illustrated in Figure 3.8.

55 See Fixed Access Network Sharing (FANS) MR-453 by the Broadband Forum.

56 See ITU-T G.989.2 40-Gigabit-capable passive optical networks 2 (NG-PON2): Physical media dependent (PMD) layer specification, Appendix 1.

Figure 3.7: Spectrum used by GPON, NG-PON1 and NG-PON2 technologies [Source: adapted from ITU-T[56]]

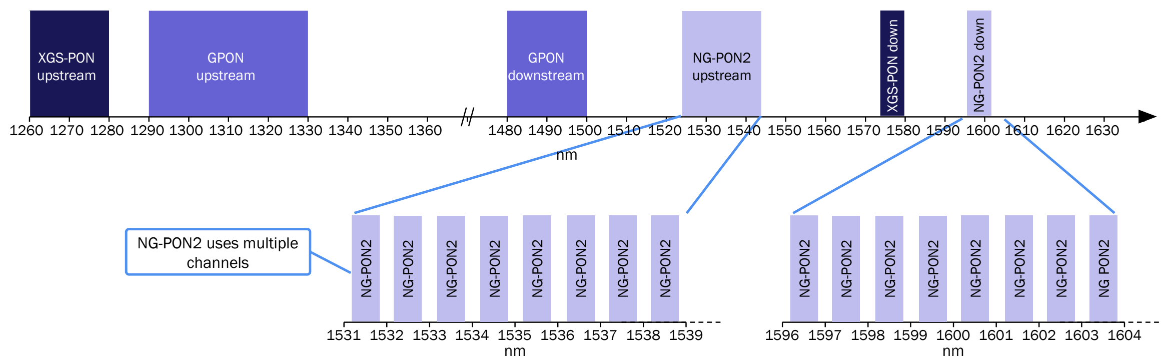
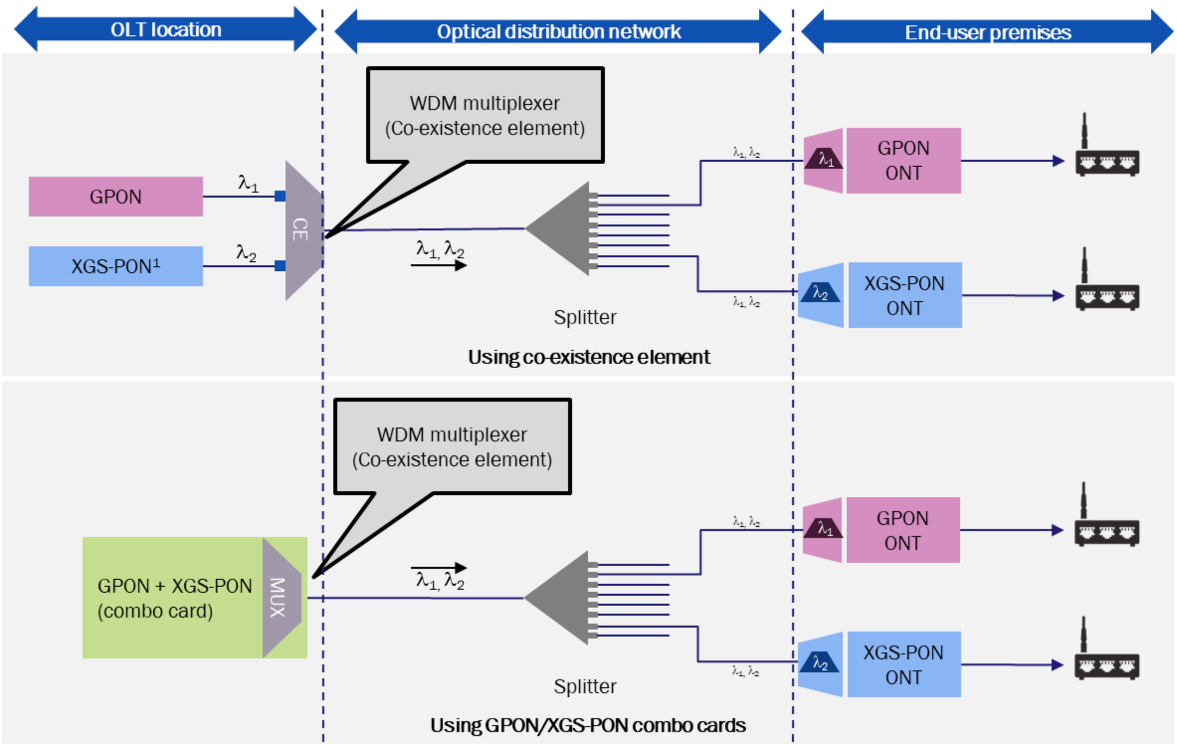


Figure 3.8: Multiplexing of GPON, NG-PON1 and NG-PON2 through the co-existence element [Source: Analysys Mason, 2022]

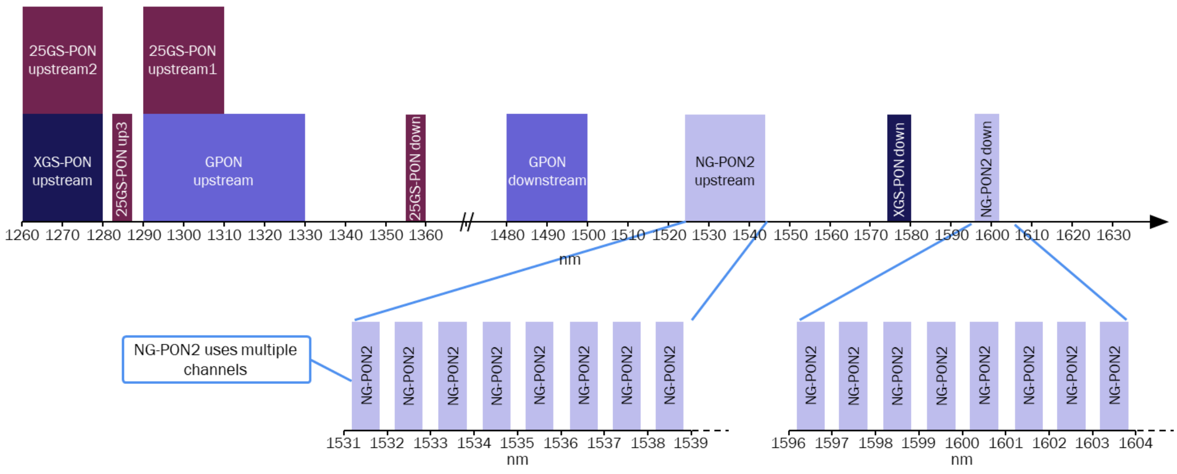


Traditionally, different GPON technologies have co-existed through the use of a co-existence element. Lately, however, combo cards that combine GPON and XGS-PON on the same port have proved popular and are offered by most equipment vendors. It is important to note the co-existence element is embedded in the combo cards. The vast majority of operators that have GPON and XGS-PON on their networks have adopted combo cards, removing the need for an external co-existence element as shown in Figure 3.8 above.

3.4.2 Co-existence of 25GS-PON

In defining 25GS-PON, the MSA industry group defined three different wavelength ranges for the 25GS-PON upstream, and one wavelength range for the downstream. This is illustrated in Figure 3.9.

Figure 3.9: Spectrum used by 25GS-PON technology [Source: Analysys Mason, Nokia, 2022]



In Figure 3.9, it can be noted that two of the upstream wavelengths (i.e. upstream 1 and upstream 2) defined for 25GS-PON are interfering with the GPON and the XGS-PON upstream wavelength respectively. In other word, if 25GS-PON is deployed using the upstream 1 wavelength, it cannot co-exist with GPON, and if it is deployed using the upstream 2 wavelength, it cannot co-exist with XGS-PON. Therefore, upstream 1 and 2 wavelengths can only be used if 25GS-PON is solely deployed with XGS-PON or GPON respectively.

However, a third 25GS-PON upstream wavelength (upstream 3) has been defined to ensure that 25GS-PON could co-exist with GPON and XGS-PON as this wavelength does not interfere with GPON or XGS-PON upstream wavelengths. It can be noted that the upstream 1 and upstream 2 wavelengths have 20nm of spectrum, whereas the upstream 3 wavelength only has 5nm of spectrum. This has significant implications since a transmitter with a narrower laser is more expensive than a transmitter with a broader laser in terms of spectrum. Upstream 3 seems to be the only upstream wavelength which will ensure co-existence of GPON, XGS-PON and 25GS-PON, but may prove more expensive than using the upstream 1 or 2 wavelength. Since it is the upstream, it means that the ONT at customer premises may be more expensive if an operator deploys a network where all three PON technologies[57] have to co-exist.

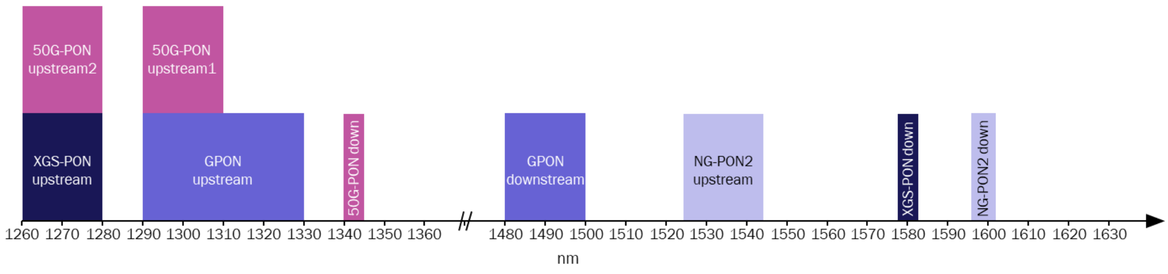
3.4.3 Co-existence of 50G-PON

However, as noted above, 50G-PON can only co-exist with **either** GPON **or** XGS-PON. Hence, it is important for operators if/when they introduce 50G-PON to have their strategy ready – i.e. remove

57 We are excluding NG-PON2 technology as it is unlikely to be widely deployed.

GPON and leave XGS-PON only (remove legacy GPON if towards end of technology life) or remove XGS-PON and leave PON only (to have a price-competitive high-speed broadband service).

Figure 3.10 Spectrum used by 50G-PON technology [Source: Analysys Mason, Nokia, 2022]



It should be noted that Huawei is currently researching how 50G-PON can coexist with GPON and XGS-PON (while keeping the same wavelength plan as specified by the ITU illustrated in Figure 3.10).

3.5 Factors affecting the adoption of PON technology

3.5.1 Competitive environment

In many markets, the adoption of the next generation of technology is mainly driven by competition and not by end-user bandwidth demand. For example, in the UK, the incumbent BT currently offers high-speed broadband products based on GPON technology and has indicated that it is not currently envisaging to upgrade to XGS-PON. The incumbent believes that GPON will support end-user traffic for the foreseeable future and therefore does not need to upgrade.

This is in marked contrast with many small new entrant operators in the UK market (such as Trooli, Toob, Wildanet and Broadway), which have deployed their FTTH network using XGS-PON to be able to provide higher-speed products than BT or than retail service providers using Openreach generic Ethernet access (GEA) products (which are also based on a GPON). Although at the moment GPON and XGS-PON are both limited by the speed of their Gigabit Ethernet interface on the ONT, operators that have deployed XGS-PON will be able to offer top tier speed services with speeds of up to 2.5Gbit/s (provided that they provide their end users with XGS-PON ONTs capable of a 2.5Gbit/s throughput), and ultimately services with up to 5Gbit/s, which will differentiate them from BT if it remains on GPON technology.

3.5.2 Bandwidth demand

Another reason for upgrading technology is that the broadband speed provided by the PON network is not sufficient to meet the demand. In this section, we therefore try to estimate when the next PON technology may be required depending on demand (and more precisely on top tier speed).

Definitions

We first define *comfort speed* as the amount of bandwidth that is required to support the typical usage at peak time of a high-end-user profile actively using the service. We also define the *top tier speed* as the maximum speed package that can be offered by an operator. For this report, we will assume that the top tier headline speed that can be provided by an operator is 40% of the aggregate speed offered by the PON to ensure that there is a minimum speed guaranteed for the end user. So for GPON, we assume that the top tier headline speed is 1Gbit/s in the downlink and 500Mbit/s in the uplink. For XGS-PON, we assume that the top tier speed that can be offered to customers is 4Gbit/s in the downlink and uplink (assuming ONTs with a 4 Gbit/s throughput will be made available).

Comfort speed estimation

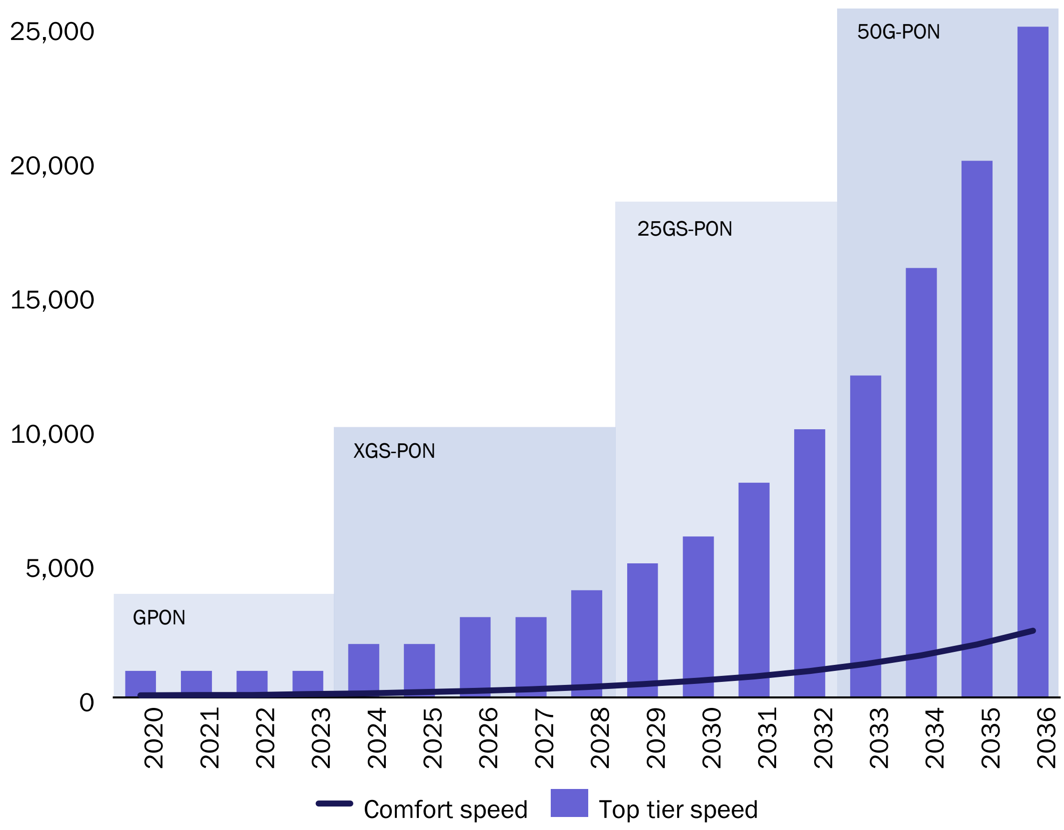
We estimate that by the end of 2022 the comfort speed requirement of the top 1% of households would be 100Mbit/s ('high-end customer'). This was verified to be a typical high user profile of:

- 2 × 4K UHD television using 30Mbit/s per stream
- 2 × HD television using 12Mbit/s per stream
- 1 × SD television using 3Mbit/s per stream
- 1 × internet browsing using 10Mbit/s.

This mix of usage results in a comfort speed requirement for high-end customers of around 100Mbit/s. In the rest of this section, we assume that the top tier speed that can be offered by an operator is 10 times the comfort speed (i.e. 1Gbit/s download speed in 2022). This assumption is in line with top-tier broadband speeds sold in the UK of 900Mbit/s and of 1Gbit/s in Ireland.

In August 2021, Analysys Mason produced a report titled 'Fixed network data traffic: worldwide trends and forecasts 2020–2026' which includes a forecast of Irish network traffic growth between 2021 and 2026. On average, it forecasts that traffic will grow at 25.8% per annum over that period. Taking the above information and assuming traffic growth continues at the same rate to 2036, the comfort speed and the top tier speed (i.e. 10 times the comfort speed) can be estimated as shown in Figure 3.11.

Figure 3.11: Analysys Mason forecast of high-end customer bandwidth requirements for Ireland vs. xPON technology which can accommodate the bandwidth [Source: Analysys Mason 2022]



Based on our assumption that the top tier speed cannot be greater than 40% of the aggregate speed offered by the technology, we can derive when different technologies will need to be required to support the needs of high-end customers (i.e. top tier speed).

Figure 3.11 suggests that XGS-PON technology will be suitable to accommodate the required top tier speed until 2028, when a top tier speed of 4Gbit/s will be needed. It can also be seen that 25GS-PON technology will be able to accommodate the required top tier speed until 2032 when the top tier speed will be 10Gbit/s. From that perspective, it appears that 25GS-PON would be a transitional technology, to address a small gap. Alternatively, operators could start deploying 50G-PON technology from 2029 to address the demand, which make sense in terms of technology lifecycle (see Section 3.5.4 for more details).

3.5.3 Technology advancement and power consumption

With the different sustainability initiatives (e.g. the European Climate Neutral Data Centre Pact (ECNDCP)) and the increase in energy price, power consumption is becoming a significant component in operators' strategy.

Intel cofounder Gordon Moore stated in 1965: *The number of transistors incorporated in a chip will approximately double every 24 months*. This is commonly known as Moore's Law. This prediction is still broadly correct today. The increase in transistor density means that, as they get closer to each other on a chip, electrons have to travel a shorter distance, making these chips both faster (by reducing latency) and more energy efficient. This in turn also means that the smaller the inter-transistor distance on a chip, the lower the heat dissipation, which means lower cooling requirements and further energy savings. It should be noted that large chip manufacturers[58] have reported spacing as low as 2nm between transistors, but we understand that these cannot yet be manufactured at scale.

Current mass-market 16nm technology

OLT GPON/XGS-PON combo cards based on 16nm chipset have a density of 16 ports per card, which seems suitable for the telecoms industry. 25GS-PON OLT cards developed on the same technology can be manufactured with a density of 8 ports per card (i.e. half of the density of combo cards) and with similar power consumption to a GPON/XGS-PON combo card. In the unlikely scenario[59] where an operator would want to deploy 25GS-PON technology at every OLT location, it would need to approximately treble the power and amount of space it currently uses in each location (i.e. existing space for combo card and twice that space again for 25GS-PON).

7nm technology (end of 2024)

The next generation of mass-market chipset will be 7nm chipset and is expected to yield a ~40% energy saving compared to the current 16nm generation. The 7nm chipset will probably enable 25GS-PON OLT cards to be manufactured with a 16-port density per card. According to some vendors, 7nm chipset will be available in Q4 2024, and commercial products (i.e. OLT cards) will be available in H1 2025. If operators choose to deploy 25GS-PON technology, it may be more advantageous to wait for the 7nm chipset technology due to the significant power saving and density benefits.

7nm will also see the development of 50G-PON OLT cards which are expected to have a density of 8 ports per card. In the same way as 16nm chipset is inefficient today for 25GS-PON, we anticipate that 7nm will not be efficient for 50G-PON technology (from a power consumption and density perspective) and may limit 50Gbit/s deployments.

2–3nm technology (between end of 2026 and 2028)

Based on interviews with equipment vendors, we believe that mass-market 2–3nm chip technology may become available by the end of 2028, which would mean that commercial products (i.e. OLT cards) would be available in H1 2029. However, we note that one of the major chip manufacturers,

58 https://newsroom.ibm.com/2021-05-06-IBM-Unveils-Worlds-First-2-Nanometer-Chip-Technology,-Opening-a-New-Frontier-for-Semiconductors

59 This scenario is unlikely as 25GS-PON is clearly not currently targeted at the residential market but provides an idea of energy consumption and space requirements.

TSMC, has announced the release of 2nm chip earlier[60] (i.e. by 2025), but we believe that it will take some time to produce this technology at scale for the telecoms industry.

The 2–3nm chipset technology will generate a 40% energy saving compared to the previous generation of chipset (i.e. 7nm) and will enable 50G-PON at the same port density as GPON/XGS-PON combo cards today (i.e. 16 ports per card).

Based on discussions with industry stakeholders, we believe that 2–3nm technology will be the real enabler of 50G-PON and large-scale deployment should result when the technology becomes available.

3.5.4 Lifecycle and return on investment

In general, telecoms equipment tends to have a lifecycle of between six and eight years[61] as operators need to ensure that the technology is in their network long enough to get sufficient return on their investment. After the end of the lifecycle, operators tend to refresh their network with the latest technology available to meet demand and reduce energy consumption.

As shown in Figure 3.12, if an operator had invested in XGS-PON technology in 2020-20222, then we would expect there to be a new investment cycle starting around 2028. For this, the operator would have two choices:

- invest in 25GS-PON, or
- invest in 50G-PON.

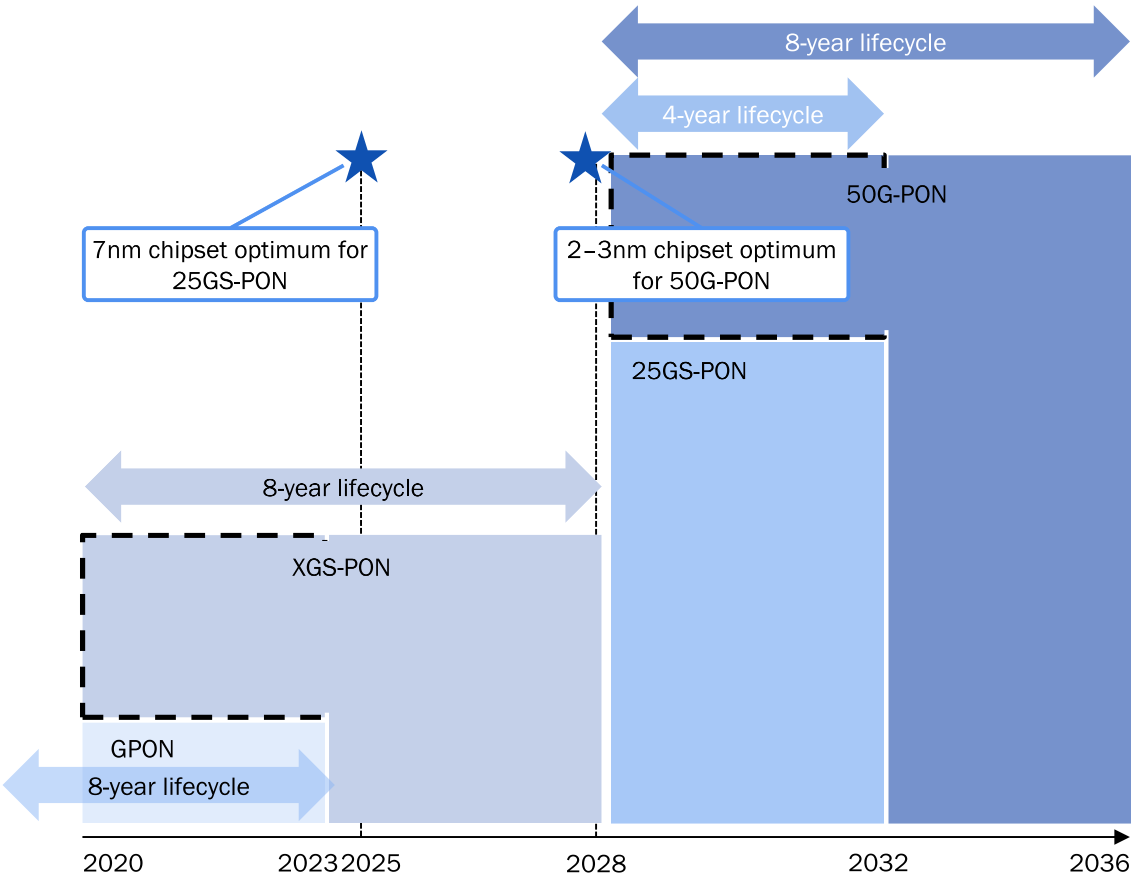
If the operator decides to invest in 25GS-PON, it is likely that it will have to re-invest in 50G-PON technology in 2032/2033 based on Figure 3.12, which would mean that the 25GS-PON lifecycle would be reduced to four or five years. Alternatively, the operator could decide to invest in 50G-PON, as, by then, the 2–3nm chipset technology should be available, which would make the deployment of 50G-PON technology efficient as argued in Section 3.5.3.

Based on the above observation, we believe that 25GS-PON will be a transition technology which may be needed to fulfil a set of niche applications (large enterprises, 5G backhaul, marketing of true 10Gbit/s broadband service), but will not be a large enough increment from XGS-PON to justify its deployment for the mass market given the expected short lifecycle and lack of standardisation from the ITU (which may mean low volumes and therefore high costs).

60 https://asia.nikkei.com/Business/Tech/Semiconductors/TSMC-says-it-will-make-ultra-advanced-2nm-chips-by-2025

61 This is in marked contrast with IT equipment, which tends to have much shorter lifecycles (three to four years).

Figure 3.12: Lifecycle of PON technology vs. chipset [Source: Analysys Mason, 2022]



4 HFC and RFoG network architecture

This section introduces a variety of concepts associated with cable networks, covering the terminology and principles required to understand hybrid fibre-coaxial (HFC) networks.

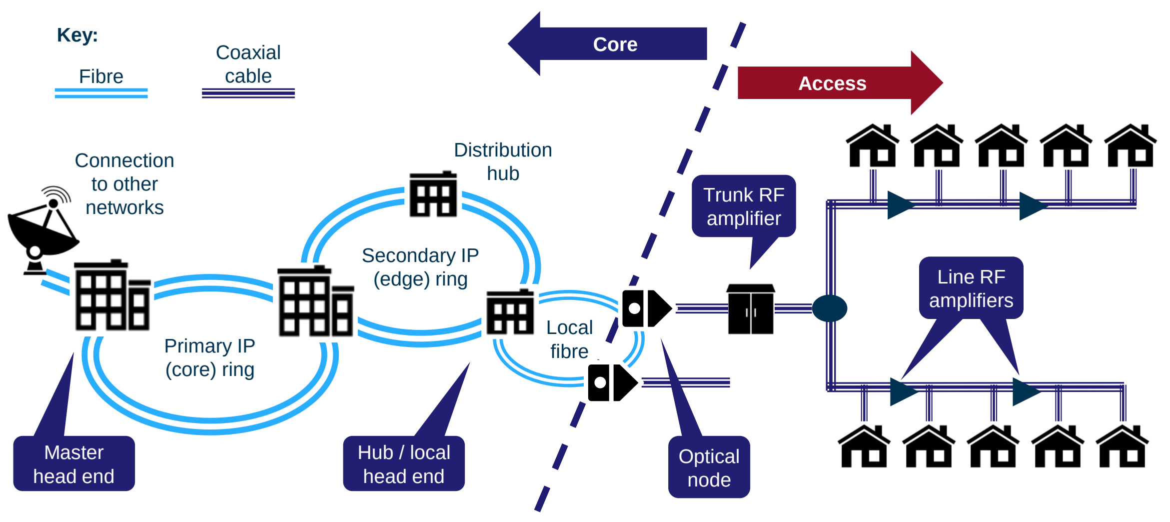
In this section we first describe the HFC concept and architecture an describe the data HFC roadmap. We then explain what an RFoG network is and provide the rationale as to why cable operators would upgrade to RFoG. Finally, we describe the factors affecting the migration of HFC/RFoG networks to PONs.

4.1 HFC concept and network architecture

HFC networks were originally designed to provide analogue and digital TV channels as opposed to traditional copper network. In addition, HFC networks were designed to provide broadband services through a technology known as data over cable service interface specifications (DOCSIS), standardised by CableLabs.

In terms of architecture, traditional HFC networks include a fibre section and a coaxial section which was delimited by the optical node (used to transform the optical signal into electrical signal and vis versa). Figure 4.1 provides a simplified diagram to illustrate the HFC network architecture.

Figure 4.1: Simplified network diagram for an HFC plant and network [Source: Analysys Mason, 2022]

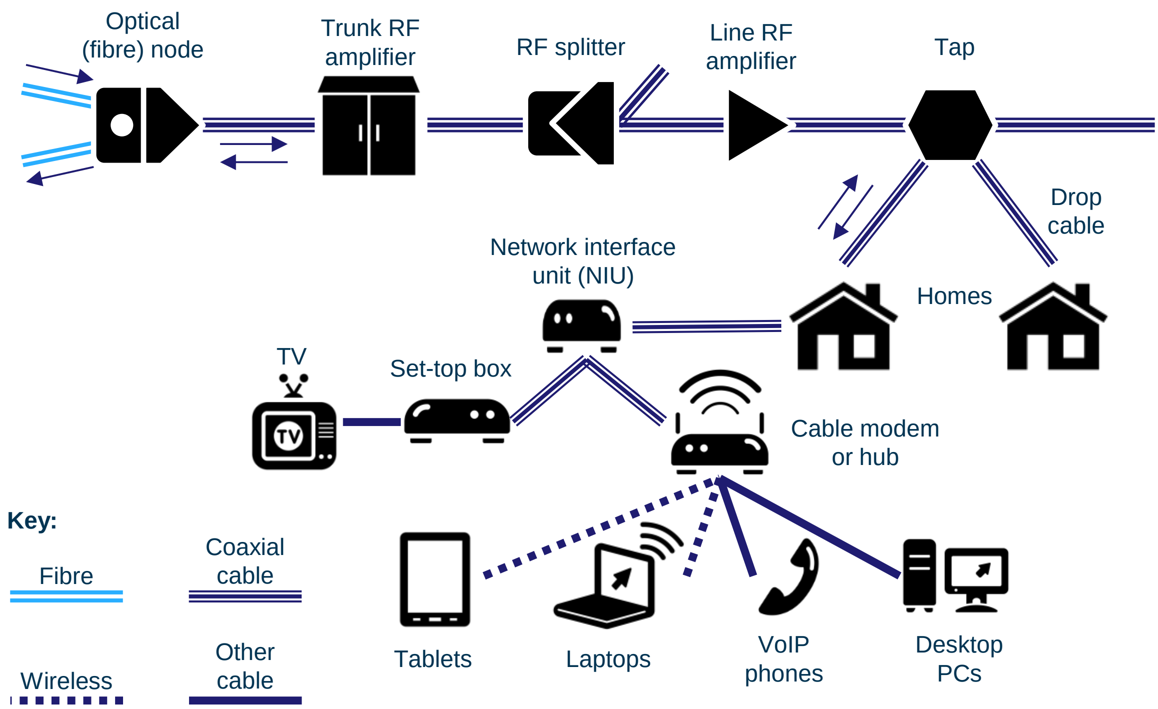


As shown in Figure 4.1, a key node in an HFC network is the master head end which is the cable operator's main network site/facility where TV and data content is aggregated and processed ready for distribution over the cable network via a local head end. The master head end frequently also includes the HFC network operations centre (NOC), which controls the operational aspects of the network. Local head ends are smaller facilities where specific local content (such as local advertising) can be added to content distributed from the master head end. Local head ends also usually contain the cable modem termination systems (CMTSs) which are used to provide data services (including VoIP) using DOCSIS. Various types of CMTS exist, and the trend is to disaggregate this equipment (i.e. distribute it closer to end users). It should be noted that more recent CMTS including the RF Video multiplexing are known as converged cable platforms (CCAP).

The core network is the central part of the HFC network, involved in the aggregation and processing of cable TV and data. It includes fibre backbone rings,[62] the master head end and the local head end.

The access network is the dispersed part of the HFC network, involved in the distribution of cable signals to end users. A more detailed illustration of the access network is provided in Figure 4.2.

Figure 4.2: Key elements of access network and home network [Source: Analysys Mason, 2022]



In the access network, the optical node acts as the optical-to-electronic converter between coaxial cable and fibre infrastructure. Optical nodes also include a radio-frequency (RF) combiner which combines a multitude of broadcast and narrowcast signals into a single stream. As the narrowcast streams (from the CMTS and video-on-demand servers) are unique for each optical node, there needs to be one combiner per optical node.

A coaxial cable tap splits out one (or more) smaller cables from a main coaxial cable, ensuring a minimal drop in signal level on the main cable. Cable taps have one input connection and multiple output connections, one of which is normally a continuation of the main cable. The secondary outputs from the tap are the drop cables, which are used to provide connectivity to individual homes. This is referred to as passive tapping losses.

62 This can be further broken down into a core ring and an edge ring.

Each time the signal passes through a tap (i.e. the signal is dropped to an end user), attenuation is incurred as a small portion of the signal power is diverted away from the main coaxial cable onto to the end user.

A line, or trunk, RF amplifier is a bi-directional active component that amplifies an RF signal[63] to overcome cable signal attenuation and passive tapping losses. These amplifiers can be powered either by external power supplies, or via a specific power supply carried along the trunk cable.

An RF splitter is similar to a cable tap, i.e. a bi-directional passive device which splits a single cable into multiple cable paths. However, unlike a cable tap an RF splitter aims to direct similar signal strengths to each of the output cables.

Finally, at the end-user premises, there are usually two types of customer premises equipment (CPE):

- cable modem
- set-top box.

The cable modem (CM) is a specific type of CPE that is used to provide bi-directional data services to a customer's premises over a cable network using DOCSIS. The CM acts as a gateway to the home local area network (LAN), connecting to a CMTS via the operator's cable network, and connecting to internal equipment (such as a computer) via an Ethernet connection. Most modern cable data systems use more complicated *cable 'hubs'*, which frequently incorporate internet firewalls, Wi-Fi connections, landline phone ports and multiple Ethernet ports.

The set-top box is the CPE that enables the demultiplexing of RF TV channels transmitted over the HFC network and modern set-top boxes include the capability to 'decode' IPTV signals which are sent as part of the data stream.

One of the main issues associated with coaxial access networks is that RF amplifiers introduce noise. When cascading several RF amplifiers on a line, additional noise is introduced at each amplifier stage and is amplified together with the signal at the next RF amplifier. Receivers (i.e. cable modems in this instance) are built to detect the signal above a certain signal-to-noise ratio. However, each time the signal traverses an RF amplifier, the signal-to-noise ratio decreases as more and more noise is added to the system. Therefore, if the signal traverses too many RF amplifiers, the signal-to-noise ratio will be too low to be detected by the receiver and the end user will not be able to get the service from the cable operator.

One solution for cable operators to overcome this issue is to shorten the coaxial section of the HFC access network to reduce the number of cascaded RF amplifiers (and therefore improve the signal - to-noise-ratio). This is typically done by pushing the fibre closer to the end user. An example of architecture leveraging such principle is known as fibre to the last amplifier (FTTLA), where cable

63 Signal on the coaxial cable.

operators have reduced the coaxial section of the access network in such a way that there is only a single RF amplifier between the optical node and any end user.

DOCSIS roadmap

As mentioned previously, cable networks use DOCSIS technology to transmit data. The first DOCSIS specification (DOCSIS 1.0) was finalised by CableLabs in March 1997. Two years later, Cisco Systems received ‘qualification’ from CableLabs for its first CMTS, and Toshiba and Thomson Consumer Electronics received ‘certification’ for the first DOCSIS-compliant cable modems.[64]

► *DOCSIS 3.1*

Today the vast majority of cable networks use the DOCSIS 3.1 standard or are in the process of being upgraded to DOCSIS 3.1. Depending on the spectrum used, DOCSIS 3.1 can provide up to 10Gbit/s in the downstream and up to 1.5 Gbit/s in the upstream, shared between all subscribers connected to that capacity pool. To achieve this aggregate throughput, the DOCSIS 3.1 standard specifies a 1.2GHz spectrum bandwidth to be used in the coaxial cable.

While the downlink bandwidth is similar to that provided by XGS-PON, the uplink speed associated with DOCSIS 3.1 is only a fraction of what XGS-PON can provide (seven times less). This limitation means that cable operators that have adopted DOCSIS 3.1 cannot offer symmetrical services in the same way as FTTP operators using XGS-PON do and could appear less competitive as they cannot market the same services.

► *DOCSIS 4.0*

DOCSIS 4.0 is the latest standard from CableLabs and enables up to 10Gbit/s in the downstream and up to 6 Gbit/s in the upstream, shared between all subscribers connected to that capacity pool. To achieve this aggregate throughput, the DOCSIS 4.0 standard specifies a 1.8GHz spectrum bandwidth to be used in the coaxial cable. DOCSIS 4.0 is a major improvement from DOCSIS 3.1 as it means that with DOCSIS 4.0, cable operators will be able to offer similar symmetrical services compared to FTTP operators using XGS-PON. It is expected that DOCSIS 4.0 equipment will be commercially available to deploy from circa 2025.

However, the increase in spectrum bandwidth from 1.2GHz required for DOCSIS 3.1 to 1.8GHz required for DOCSIS 4.0 means that upgrades to DOCSIS 4.0 require the replacement of all RF amplifiers, taps, and possibly wall outlets as existing equipment (previously compatible with DOCSIS 3.1) was manufactured for a 1.2GHz spectrum bandwidth.

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64 Note: CPE is tested for ‘certification’, while CMTS equipment is tested for ‘qualification’.

Evolution of HFC network to RFoG

As explained in the previous section, there is a requirement to shorten the coaxial section of the network due to the signal-to-noise ratio. Also, as DOCISIS technology evolves to enable the provision of increasingly higher bandwidth services to end users, a gradually larger portion of the coaxial spectrum is required to accommodate the latest release of the DOCSIS standard. However, high-frequency signals in coaxial cables are subject to more attenuation and other distortion effects than low-frequency signals, which means that the coaxial section of the cable may also need to be reduced in length as the cable operator upgrades to the latest DOCSIS version.

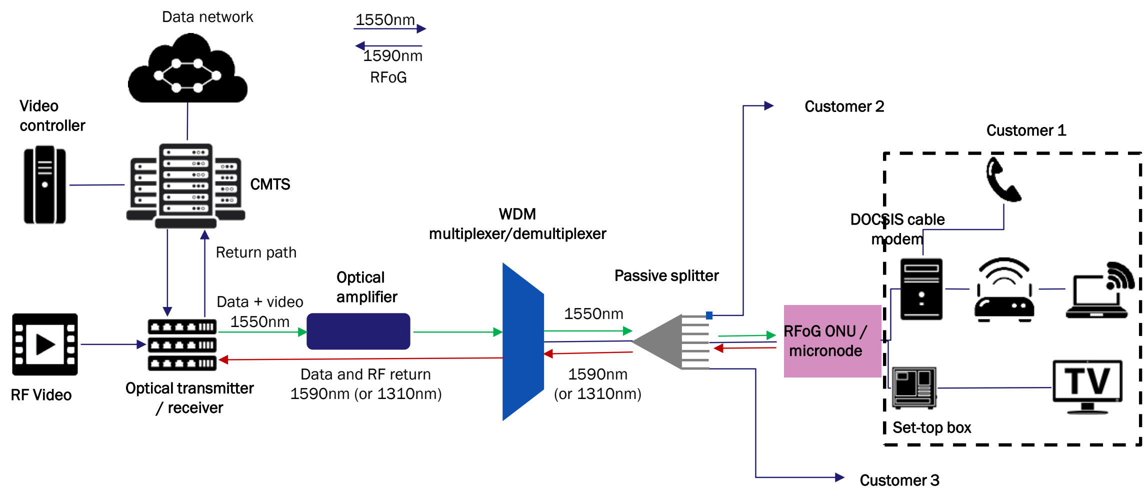
Therefore, as the demand for bandwidth increases and competition with FTTH operators intensifies, cable operators have had to upgrade their networks by deploying fibre progressively closer to the end user to alleviate the limitations associated with coaxial cables mentioned above. As a result, many cable operators have now deployed deep fibre infrastructure (i.e. completely replaced the coaxial cable section with fibre all the way to the end user). Such networks are known as RFoG networks.

4.2 RFoG network architecture

Since all coaxial cable has been replaced with fibre, an RFoG network can be considered as an FTTH network with HFC technology. In an RFoG network, all signals (downstream and upstream) have to co-exist on the same fibre all the way to the end user. In order to achieve this, the head-end transmit and receive signals are converted to different wavelengths so that they do not interfere with each other.

We describe below an example of RFoG implementation. In our example, it is assumed that video controllers and data networking services (including IPTV streams) are first multiplexed through a CMTS/CCAP router. Then, the CMTS/CCAP router output is multiplexed with the RF video signals through the RF combiner. The output signal from the RF combiner is then converted into a wavelength (1550nm in this example) using an optical transmitter system. The signal can then be optically amplified using an erbium doped fibre amplifier (EDFA)_ amplifier if required (depending on the distance between the optical transmitter equipment and the end users). Downstream traffic is then multiplexed onto the same fibre as the one used to receive the signal from end users using a WDM multiplexer/demultiplexer. The transmitted signal then passes through a passive splitter (same device used in PON networks), which is replicated to all end users connected to that splitter. The signal then reaches the RFoG CPE located at the end-user premises, also known as the micro-node. The micro-node terminates the fibre connection and converts the traffic for delivery over the in-home network. RF TV channels and IPTV streams are fed to the TV set-top box, and voice and data traffic can be delivered to the cable modem equipment. The return path (i.e. signal from the micro-node to the head end) for voice, data, and video traffic is usually sent over a 1310nm or 1590 nm wavelength to an optical receiver located in the head end, which converts the optical signal and feeds it back into the CMTS (return path). This is illustrated in Figure 4.3.

Figure 4.3: Example of RFoG configuration [Source: Analysys Mason, 2022]



As mentioned above, there are two options for the return wavelength on the RFoG network: 1310nm or 1590nm. A 1310nm return wavelength is slightly lower in cost than a 1590nm return wavelength, but 1310nm conflicts with the GPON and 50G-PON upstream wavelengths as described in Section 3.4. Therefore, to enable a smooth migration to PON, it is important that 1590nm is used for the return path (and not 1310nm).

In terms of fibre architecture, there are two options for RFoG:

- tapped architecture
- dropped architecture (same as PON networks and assumed in Figure 4.3).

Tapped architecture emulates the HFC tapping architecture (see description of tap in Section 4.1), but it does require continuous design effort to select the appropriate tap values for each serving area, and there could be operational challenges to insert/add new homes at a later date. Also this architecture is not really in line with PON architecture where splitters are centralised.

The dropped fibre architecture (which we assumed in our example) can be described as a PtP network from the splitter, where each end user has a dedicated fibre between the splitter and their respective premises. This is the same fibre architecture being deployed for PON today so lends itself well to future PON migration.

4.3 Factors affecting the migration to PON

Liberty Global's strategy

Liberty Global's CEO indicated in August 2021 that cable and DOCSIS technology will continue to play a key role in its networks for years to come, but its strategy will differ according to its country of operation based on local competition, capex investment and available network infrastructure.[65] Liberty Global is not intending to decommission its cable network in the UK in the short-to-medium term, but instead plans to use DOCSIS 3.1 to offer speeds of up to 2.2Gbit/s to end users. We interpret this to mean that it plans to update the UK cable network to RFoG, keeping DOCSIS 3.1 and all other HFC-related equipment in its network. Liberty Global also indicated that Ireland is very similar to the UK in terms of strategy, meaning that it is probably planning to upgrade its cable network to RFoG in Ireland. In the same interview, Liberty Global's CEO recognised that, while there is a clear path to 50Gbit/s with the 50G-PON standard, the DOCSIS roadmap does not currently offer such a futureproof standard, which would indicate that, in the long term, the only available option to remain competitive for cable operators will be to upgrade to PON.

Availability of infrastructure

A key factor affecting the timeframe as to when a particular cable operator might migrate to PON is the availability of duct infrastructure. After DOCSIS 3.1 is implemented, cable operators will face a critical strategic choice for their next upgrade: either upgrade to DOCSIS 4.0 or migrate directly to FTTP PON technology. We believe that such a decision will be required in four to six years from now as DOCSIS 4.0 will not be available for commercial deployment before 2026 and DOCSIS 3.1 will be able to address the market demand till then. DOCSIS 4.0 extends the life cycle of HFC equipment and is a good candidate to compete with XGS-PON in terms of offering symmetrical services. A DOCSIS 4.0 upgrade would involve the replacement of disaggregated CMTS and of all cable modems at end-user premises, which could be costly. For cable operators still with some coaxial cable in their access network (i.e. that have not transited yet to RFoG), an upgrade to DOCSIS 4.0 would also require the replacement of all RF amplifiers (if any) and of all taps.

Upgrade to PON requires the deployment of additional fibre cables in the access network. In countries where cables are mostly buried, such the Netherlands and Germany, extensive civil works are required to install these additional fibre cables, making the upgrade significantly more expensive than upgrading to DOCSIS 4.0. Therefore, in countries where the availability of duct infrastructure is low, cable operators may elect to deploy DOCSIS 4.0 as an intermediate step before upgrading to PON.

In other countries where duct infrastructure is available, the deployment of additional fibre cables for the PON upgrade is significantly less expensive that in countries where there are few ducts available because additional fibres can just be pulled through existing ducts and very little digging up is required. Therefore, in countries where duct infrastructure is available, cable operators may elect to upgrade directly to PON, without taking the intermediate step of investing in DOCSIS 4.0 technology.

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65 https://www.fiercetelecom.com/operators/liberty-global-ceo-says-its-not-done-docsis-yet

End-user equipment

Another factor affecting the decision to migrate to PON is the requirement to replace the set-top box in the cable operator's network. If the set-top box currently installed at end-user premises is IP capable, then it will be compatible with IPTV signals received on the PON and therefore the set-top box will not need to be replaced. We understand that Liberty Global's strategy has been to install IP-capable set-top boxes allowing IP broadcast and narrowcast, making it easier to transit to PON when the operator decides to do so.

Some cable operators may take the additional DOCSIS 4.0 step to extend the life of their HFC/RFoG infrastructure where it makes economic sense. However, given that the DOCSIS roadmap does not yet[66] provide any upgrade path beyond 10Gbit/s, we expect that cable operators will all ultimately have to upgrade to PON architecture, the timing of which will depend on local market competition, capex investment required and the availability of duct infrastructure.

[66] There have been discussions in CableLabs about extending upper spectrum to 3.0GHz, which would provide a 20Gbit/s bandwidth in the downlink and 6Gbit/s in the uplink. However, no formal standardization effort exists.

5 ODN sharing models

There are different ways to share on ODNs between operators depending on the network's open systems interconnection (OSI) layer considered:

- passive sharing (dark fibre)
- PON wavelength sharing
- wavelength overlay
- RFoG ODN sharing
- Layer 2 active sharing (virtual unbundled access or VUA, and Bitstream)
- network slicing (SDN and NFV/FANs).

We describe each of these ODN sharing mechanisms in the following subsections and assess their operational and commercial limitations.

5.1 Passive sharing (dark fibre)

Description

In order to illustrate passive ODN sharing, we consider the case of dark-fibre unbundling in France for the public initiative networks (PINs). Due to the lack of private investment to roll out FTTH in rural areas in France, French local authorities have set up regional subsidised PINs for which infrastructure operators have to compete to be awarded the contract. The PIN framework is based on a contract between the successful bidder (future wholesale operator) and the local authority.

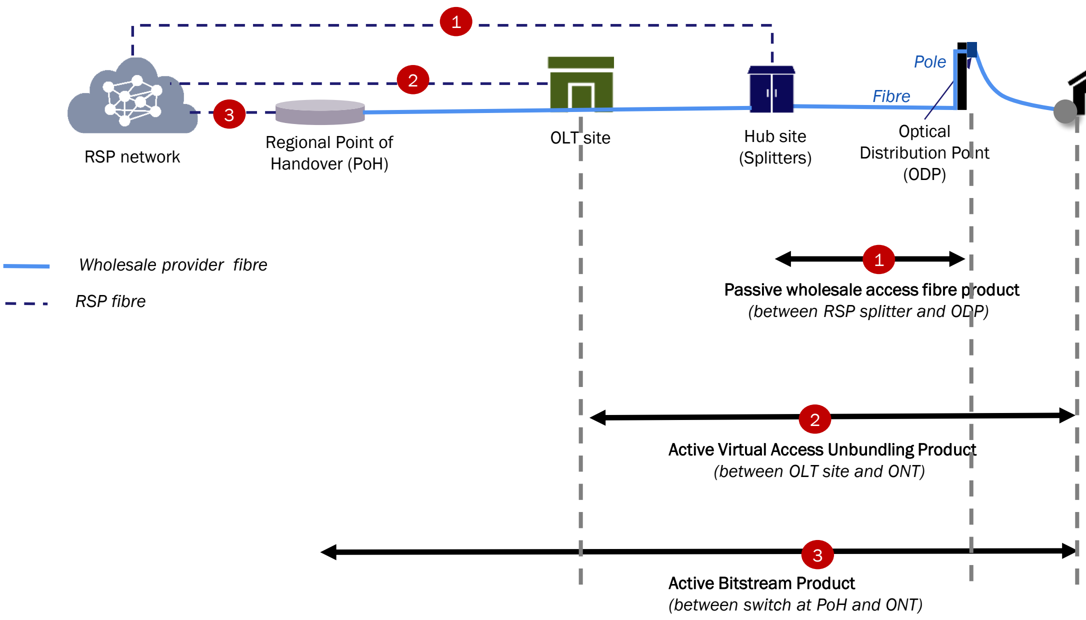
In Ireland, the equivalent scheme is known as the National Broadband Plan (NBP) where wholesale operator NBI is subsidised by the government to deploy a wholesale FTTH network in rural Ireland.

PINs are deployed as wholesale-only open-access networks and provide a number of wholesale services input for access seekers to purchase and offer end-to-end broadband services to their own customers. The services offered by wholesalers in the PIN usually include:

- passive access products (vast majority of wholesale products)
- Layer 2 VUA (discussed in Section 5.5)
- Layer 2 Bitstream (discussed in Section 5.5).

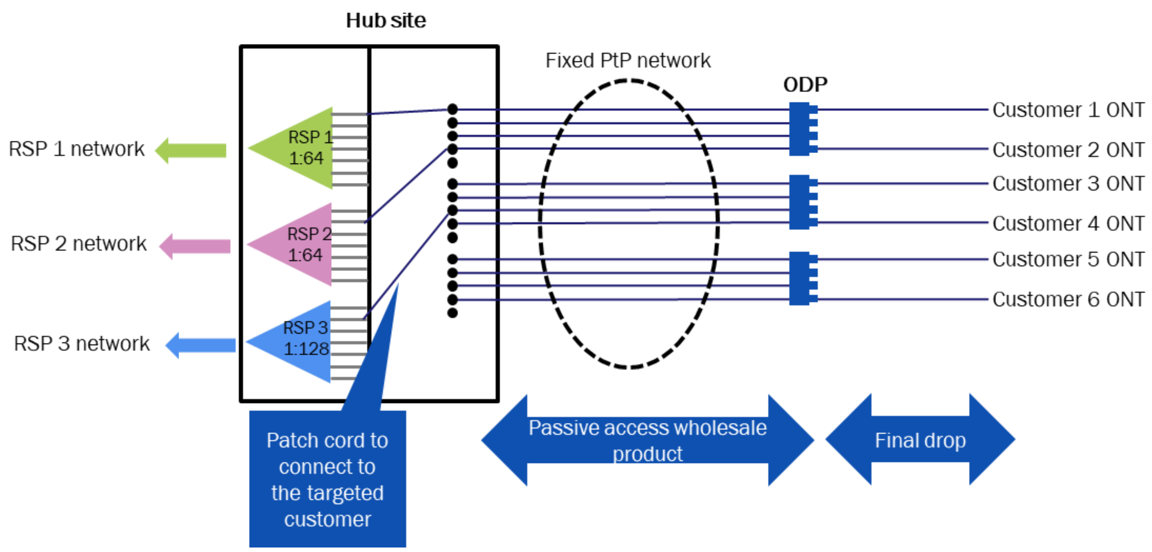
The vast majority of wholesale products in PINs are based on **passive access products** which provide a dark fibre from the hub site to the optical distribution point (ODP). This is illustrated in Figure 5.1 (case 1).

Figure 5.1: Wholesale products in French PINs [Source: Analysys Mason, 2022]



In the context of ODN sharing, it means that the fibre between the hub site and the ODP is effectively shared and no overbuild is required on that part of the PON. Access seekers deploy their own splitters at hub sites and then use the hub site cabinet patch panel to connect the output of their splitter port to the input of the dark fibre serving the targeted customer as illustrated in Figure 5.2.

Figure 5.2: Example of physical connection in ODN passive sharing [Source: Analysys Mason, 2022]



As shown in Figure 5.2, access seekers (denoted RSP 1, 2 and 3 in the above figure) have to connect to their own network at the hub site. It can also be seen that different access seekers have to install their own splitters in the hub site which can be of different split ratios giving them full flexibility to define their own broadband retail products and they are free to select their own PON OLT technology (i.e. GPON or XGS-PON or other). Therefore, access seekers are not limited in any way by the wholesale provider.

Operational and commercial limitations

The PIN model requires a hub site cabinet to be deployed to provide the interconnect between the wholesaler and access seekers and the cost of supplying and installing such cabinet is in the region of EUR10 000–15 000. Since such cabinets usually cover areas of ~300 premises, it adds a significant cost per end user, especially in areas of low penetration.

The PIN model has also been prone to operational issues as all access seekers offering retail services using the wholesaler's ODN have their own splitters installed in the hub sites, and do not always follow best industry practice in terms of connecting their splitters to the dark fibre rented from the wholesale operator. This has led to significant issues associated with the management of the fibre cables (i.e. patch cords) within the hub-site cabinet, as illustrated in Figure 5.3 below. The mis-management of fibre within the hub-site cabinet could lead to a number of issues, for example significant increase in the number of network faults as it is difficult to identify which fibre is connected to which port in the hub site.

Figure 5.3: Example of a hub site with multiple access seekers [Source: Analysys Mason, 2022]

Specific to French PINs is the ability for access seekers to co-invest (together with the PIN wholesale provider) in the fibre between the hub site and the ODP. In this case, the monthly rental fee for the access seeker is significantly reduced as it only includes the maintenance costs of the fibre.

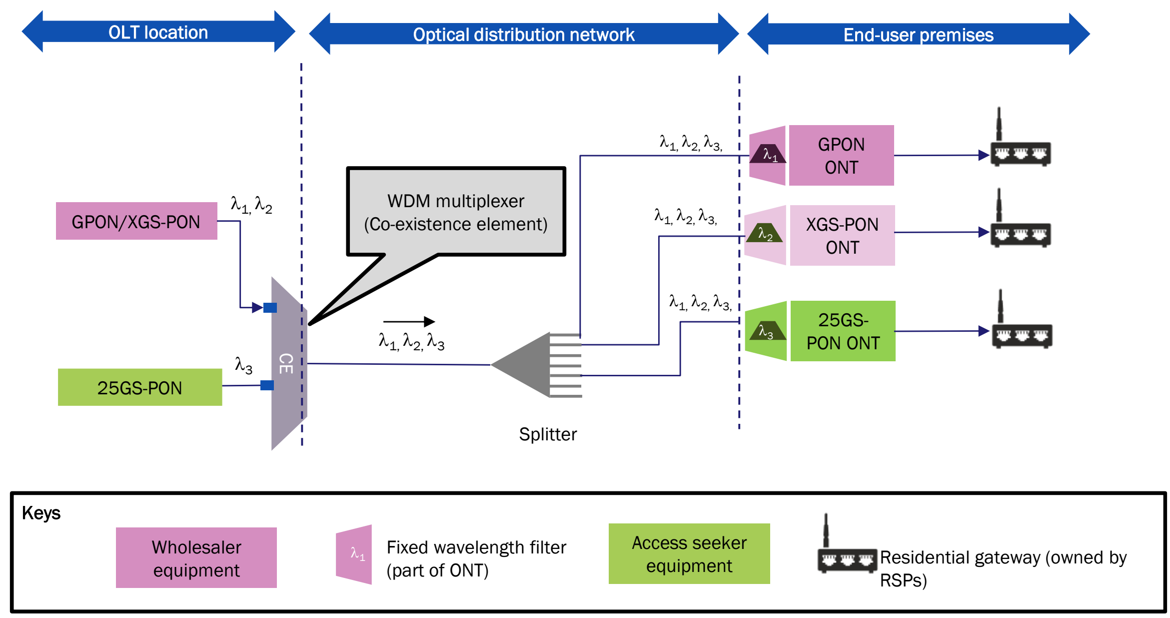
5.2 PON wavelength sharing

Description

As explained in Section 3.4, different PON technologies have been assigned different wavelengths so that they can all co-exist on the same ODN.[67] In this context, TWDM-PON was the most appropriate technology for ODN sharing as it allowed up to eight different access seekers to share the ODN (each using different wavelengths). However, as described in Section 3.3.3, TWDM-PON was never deployed at scale due to the high cost of the solution. TWDM-PON is therefore not a viable solution for ODN sharing.

Let us now examine the case where an access seeker would want to transmit 25GS-PON or 50G-PON over a shared ODN network. For this example, let us assume that the wholesale operator has deployed GPON/XGS-PON combo cards in its network (which is common practice). It is theoretically possible for an access seeker to use the wholesaler's ODN to transmit 25GS-PON (or 50G-PON when it becomes available). Figure 5.4 illustrates the ODN sharing with 25GS-PON technology and Figure 5.5 illustrates the ODN sharing with 50G-PON technology.

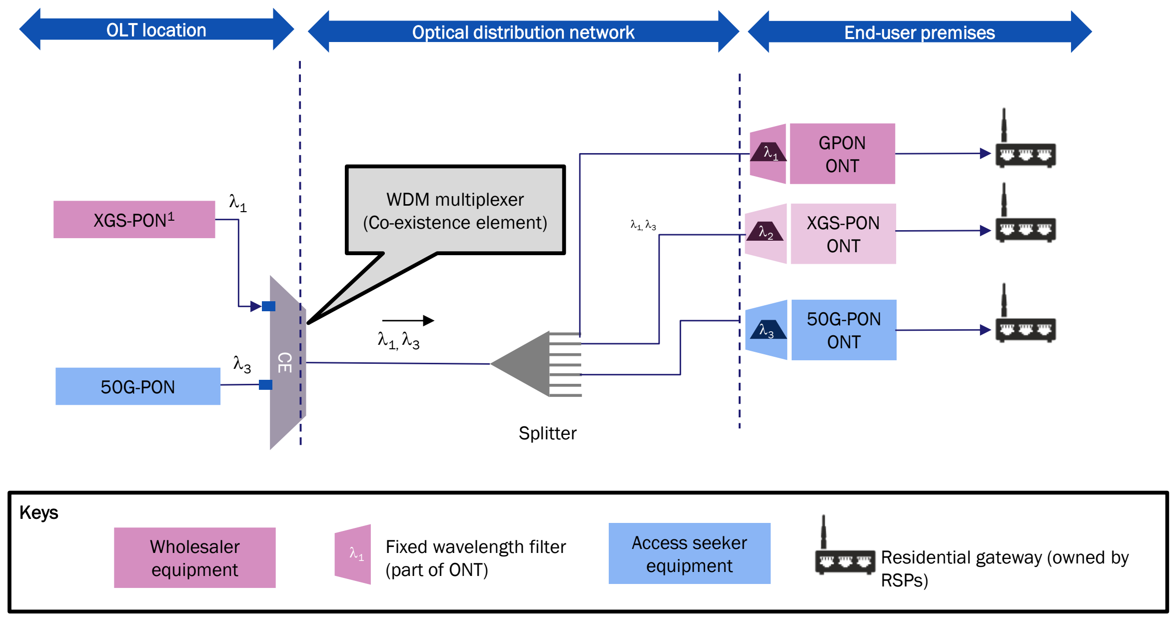
Figure 5.4: 25GS-PON ODN sharing example [Source: Analysys Mason, 2022]



Only the downstream wavelength is shown for clarity

[67] With the exception of 50G-PON.

Figure 5.5: 50G-PON ODN sharing example [Source: Analysys Mason, 2022]



[1] Could also be GPON instead
Only the downstream wavelength is shown for clarity

► *25GS-PON ODN sharing*

In the case of 25GS-PON ODN sharing, there is a number of sub-scenarios in terms of how the wholesale service could be offered:

- Case 1: the wholesaler uses a 25GS-PON compatible chassis (e.g. Nokia FX OLT platform) and adds 25GS-PON cards to its own equipment
- Case 2: the wholesaler uses a platform which is not compatible with 25GS-PON technology and the access seeker uses its own 25GS-PON OLT.

In **Case 1**, the wholesaler would just add a 25GS-PON OLT card to its existing OLT and connect its GPON/XGS-PON combo cards and the 25GS-PON card to the co-existence element to allow GPON, XGS-PON and 25GS-PON to co-exist on the ODN. The wholesaler would retain the control of the entire ODN as its operational support system (OSS) would control GPON, XGS-PON and 25GS-PON technologies. The 25GS-PON wholesale product would consist in a Layer 2 managed service, with an interconnection between the wholesaler and access seeker through a Layer 2 switch. In customer premises, the wholesaler would provide each of the access seeker's customers with a 25GS-PON ONT. This is in effect equivalent to the Layer 2 active ODN sharing model presented in Section 5.5.

In **Case 2,** the access seeker would own the 25GS-PON OLT. The wholesaler would make its co-existence element available to the access seeker to allow for GPON, XGS-PON and 25GS-PON to co-exist on the same ODN. In this case, the access seeker would also need its own OSS system to be able to configure and operate its 25GS-PON over the shared ODN. The access seeker's 25GS-PON OLT could either be co-located at the wholesaler local exchange or in a cabin/cabinet owned by the RSP close to the wholesaler local exchange. In customer premises, the access seeker would need to provide each customer with a 25GS-PON ONT.

- *50G-PON ODN sharing*

Essentially the same scenarios as above apply for 50G-PON with the exception that the wholesaler would have to disable either GPON or XGS-PON on its combo cards and replace all installed ONTs of the disabled technology since 50G-PON cannot co-exist with both GPON and XGS-PON at the same time, as explained in Section 3.4.3.

Operational and commercial limitations

As the wavelength of the xPON technology (i.e. 25GS-PON or 50G-PON) used by the access seeker cannot be used twice, sharing of the ODN is only possible for a single access seeker, which is very limiting in a competitive market. Also, due to the same reason as above, it will not be possible for the wholesaler to deploy the xPON technology which has been deployed by the access seeker (i.e. the wavelength is already used). Finally, we believe that if the access seeker were to deploy 50G-PON technology, the wholesaler would have to disable either its GPON or its XGS-PON, which is not practical.

5.3 Wavelength overlay

Description

Wavelength overlay consists in using WDM technology to transmit a signal in an ODN using a wavelength that is not already used (or reserved) by the PON technologies between the OLT site and end users connected to the PON network. This is very similar to the WDM-PON technology referred in Section 3.3.3 where the overlay wavelengths are added to an ODN and co-exist with all other PON technologies.

The main differences between WDM-PON and overlay wavelengths is that in the latter case, only a few overlays (e.g. up to 8) would be deployed to address specific end users or application requirements, while the rest of end users will be served by standardised xPON technology.

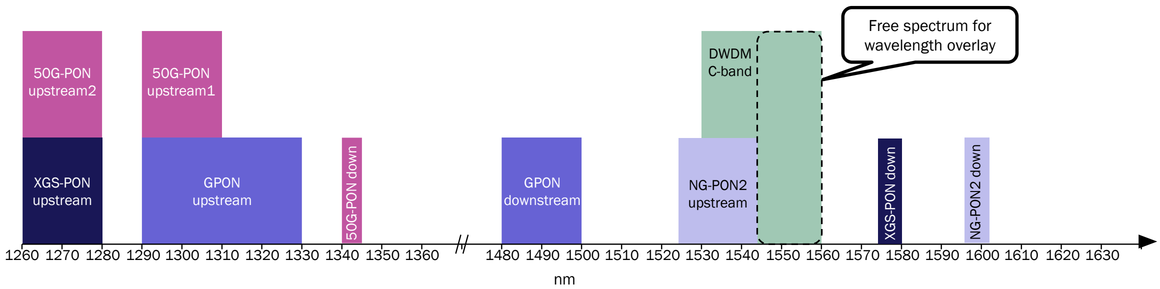
Overlay wavelengths could offer different speeds i.e. 10Gbit/s or 25Gbit/s to address different applications such as large enterprise connectivity and 5G small-cell backhaul.

While the overlay wavelength solution is not standardised, research currently focuses on providing DWDM wavelengths in the C-band (1528 nm to 1565). Overlay wavelengths could be deployed using a portion of the C-band spectrum (i.e. between 1545nm and 1565nm) if vendors want to preserve the ability for operators to be able to use NG-PON2. Alternatively, vendors could provide overlay wavelength over the full C-band, assuming that NG-PON2 will never be deployed to increase the number of overlay wavelengths. This is illustrated in Figure 5.6. It should also be noted that since ODNs are single fibre systems, two wavelengths per overlay channel will be required (one for the downlink and one for the uplink). If using a 100GHz grid (see Annex A for detailed explanation), each wavelength has a ~ 1nm spectrum[68] meaning that:

- If the full C-band is used (i.e. 36nm), approximately 36 wavelengths could be made available which means that **up to 18 bi-directional channels could be made available**.
- If only using the free spectrum (25nm) in the C-band (i.e. not using the spectrum reserved for NG-PON2), approximately 25 wavelengths could be made available which means that **up to 12 bi-directional channels could be made available**.

In reality, each PON will only include a maximum of 32 (or 64[69]) end users and only a small subset of these end users (i.e. large enterprises, 5G small cells, etc.) will need a wavelength overlay. Therefore, we believe that systems with eight overlay wavelengths might be sufficient in most cases.

Figure 5.6: Availability of wavelength spectrum in PONs [Source: Analysys Mason, 2022]



In the same way as xPON technologies are 'broadcast' to all end users connected to the ODN, overlay wavelengths would also be transmitted to all end users and the end user with the correct wavelength filter on the CPE would filter out the wavelength destined for it.

In terms of ODN sharing, there would be two potential scenarios with wavelength overlay:

- Case 1: the wholesaler provides the overlay wavelength using its own equipment.
- Case 2: the access seekers own the wavelength overlay equipment and connects to the wholesaler co-existence element (WDM multiplexer/demultiplexer).

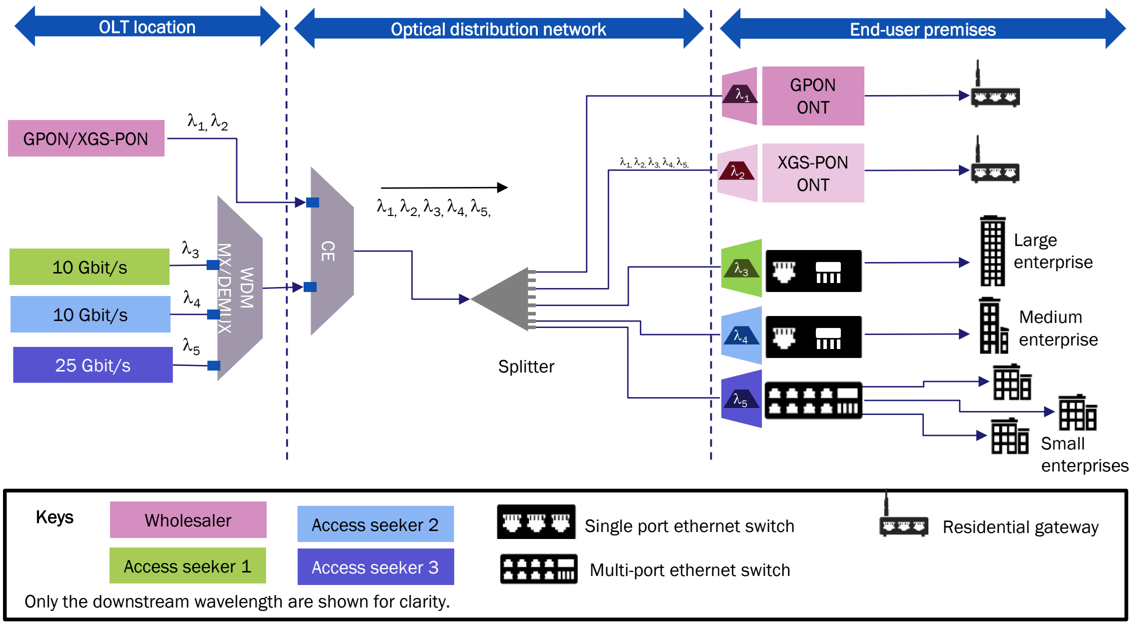
In **Case 1**, the wholesaler would just add overlay wavelengths to its existing ODN, providing a wholesale 10Gbit/s or 25 Gbit/s wavelength service, with an interconnection between the wholesaler and access seeker through a switch located at the point of handover between the access seeker and the wholesaler. In customer premises, the wholesaler would provide each of the access seeker's customers with a small WDM CPE made of a WDM multiplexer/demultiplexer and a WDM transponder to encode the signal into the correct wavelength on the uplink. This is illustrated in Figure 5.7. We note that in order to keep the cost down, fixed wavelength transponders would be preferable compared to tuneable wavelength systems.

68 Including guard bands to filter out each wavelength.

69 Depending on the split ratio.

In **Case 2,** the access seeker would own the WDM equipment (known as a transponder). The wholesaler would make WDM multiplexer/demultiplexer equipment available to the access seeker to connect its overlay wavelength(s) to the ODN. In this case, the access seeker would need its own OSS system to be able to configure, operate and manage its WDM system. The access seeker's WDM equipment could either be co-located at the wholesaler's local exchange or in a cabin owned by the access seeker close to the wholesaler's local exchange. In customer premises, the access seeker would need to provide each customer with a switch comprising integrated WDM transmitters and WDM multiplexer/demultiplexer. Finally, it should be noted that in this case, the 10Gbit/s or 25Gbit/s overlay wavelength could be used by the access seeker to provide service to a single end user (i.e. large enterprise) or to several end users as illustrated in Figure 5.7.

Figure 5.7: Example overlay wavelengths ODN sharing [Source: Analysys Mason, 2022]



As mentioned above, with this model it would be possible for the access seeker to target densely populated residential areas by installing a multiport switch in a cabinet or in the basement of an MDU building for instance and extend connection to end users from that switch.

Operational and commercial limitations

This solution is not yet commercially available for ODNs, but ADTRAN is actively researching this technique to provide 10Gbit/s or 25 Gbit/s connectivity to large enterprises or 5G small cells without having to resort to 25GS-PON.[70] This solution is further facilitated by the merger between ADTRAN and ADVA which is an optical equipment manufacturer which produces, among other equipment, WDM equipment.

70 https://www.fiercetelecom.com/telecom/adtran-thinks-wavelength-overlay-not-25g-will-be-pons-next-step-forward

We believe that this solution could become available in the short term (i.e. early 2023) as it uses DWDM technology which has been available for more than two decades.

We do not see the cost associated with such model being a major barrier as the technology is very mature and it is targeted at large enterprises and 5G backhaul which command a significantly higher revenue that residential customers.

Ultimately, the wavelength overlay model would be limited by the fact that it is not standardised especially in the context of ODN sharing. One way around standardisation is to re-use the same wavelengths as the ones used for NG-PON2, assuming NG-PON2 will never be deployed.

5.4 RFoG ODN sharing

Description

As described in Section 4, a number of cable operators around the world are upgrading their cable networks to extend the fibre all the way to end users to eliminate the limitations associated with coaxial cable. Many cable operators have therefore implemented an RFoG architecture to leverage existing equipment present in the cable network (including head-end equipment).

In this section, we consider the feasibility for a cable operator to access a PON ODN network of a wholesale provider to extend its RFoG footprint.

We consider two specific cases:

- **Case 1:** Use of the shared ODN for both DOCSIS data and RF TV channels
- **Case 2:** Use of the shared ODN for just RF TV channels.

The architecture for Cases 1 and 2 is illustrated in Figure 5.8 and Figure 5.9 respectively.

Figure 5.8: ODN sharing for DOCSIS data and RF TV channels [Source: adapted from Commscope/Arris, 2022]

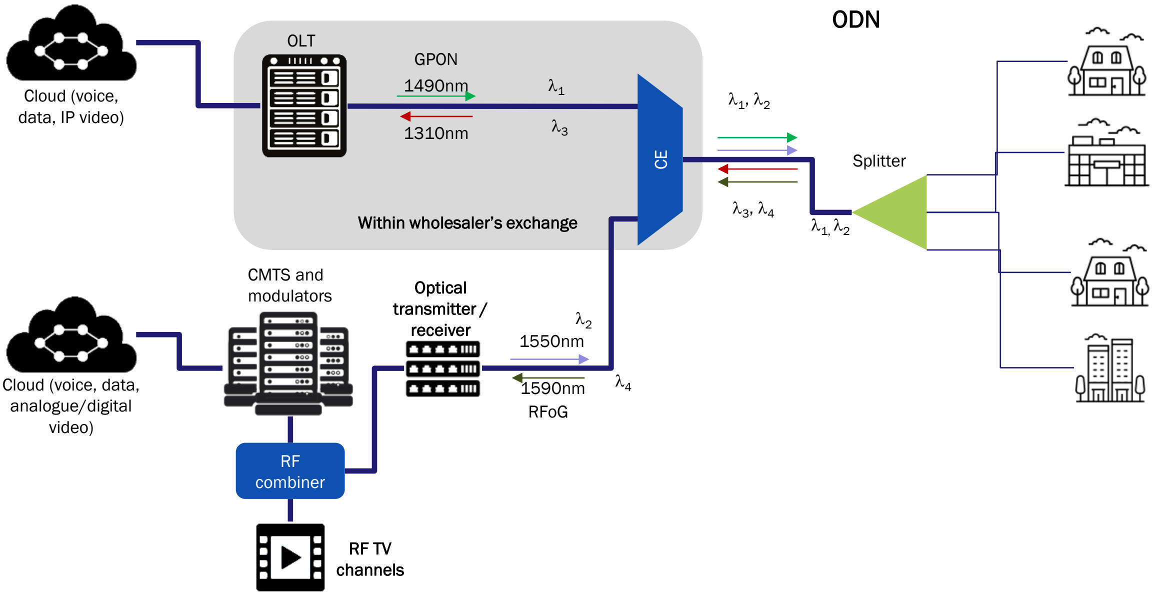
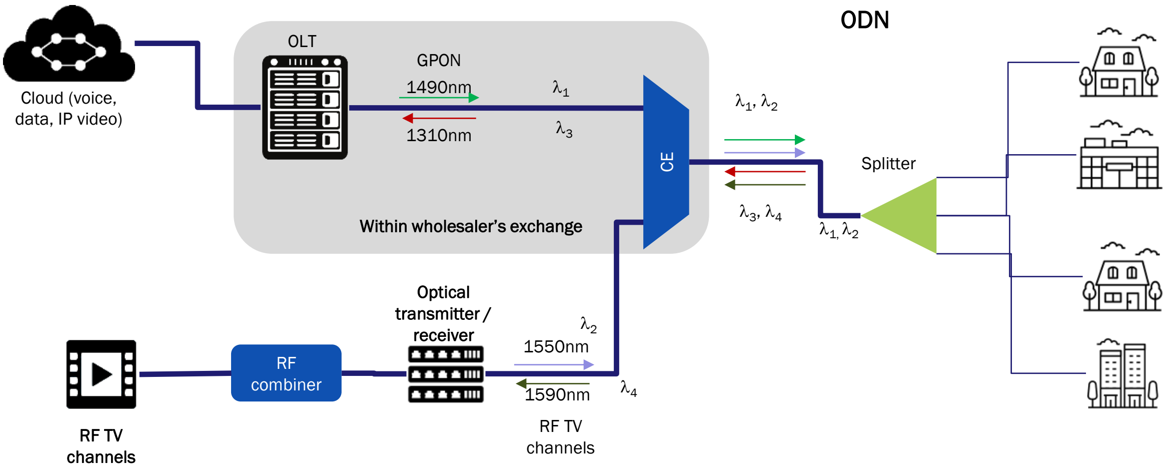


Figure 5.9: ODN sharing for RF TV channels [Source: Analysys Mason, 2022]



As described in Section 4.2, since the RFoG can be transmitted over a set of wavelengths which do not interfere with xPON technologies, it is technically possible for the RFoG system to co-exist alongside the xPON technology on the same ODN, provided the RFoG return wavelength selected by the cable operator is 1590nm and not 1310nm. At the end-user premises, an RFoG micro-node or an ONT with an RF output port would be required to filter out the RF signal.

Operational and commercial limitations

We believe that there are commercial limitations for cable operators to share ODNs:

- XGS-PON-based wholesale service has the potential to be superior to broadband services which can be offered by DOCSIS 3.1, especially for the uplink
- potential topology misalignment between cable network and the ODN in terms of equipment location
- replacement of RF TV channels by IPTV and OTT content.

In markets where XGS-PON technology has been deployed by the wholesaler(s), VUA and Bitstream wholesale services based on that technology can be provided to access seekers. XGS-PON is capable of delivering symmetrical multi-gigabit wholesale services, provided that the wholesaler upgrades its end-user ONT to provide 2.5Gbit/s throughput to end users.[71] DOCSIS 3.1 cannot replicate this symmetrical throughput, and therefore from a competition perspective, cable operators may choose to rent a VUA or Bitstream wholesale service based on XGS-PON rather than renting the shared ODN to provide DOCSIS 3.1-based broadband services. We also note that, for greenfield deployment, many cable operators have directly implemented XGS-PON (and not RFoG), which supports this argument.

The network nodes in the wholesaler's network and in the cable operator's network do not necessarily align geographically. If a cable operator were to share the wholesaler's ODN, it may need to co-locate its DOCSIS equipment within the wholesaler's handover points, which may be far away from end users (assuming that only some of the regional exchanges used to host the OLT qualify to be wholesale handover points) and therefore would require optical amplification. Optical amplification will increase the cost of providing the service for the cable operator and may cause no linear effects to other signals in the ODN on different wavelengths.

Historically, a significant differentiator for cable operators compared to incumbent operators has been the offering of analogue and digital RF TV channels. In the USA and in Germany, some cable operators that have adopted PON technology transmit RF TV channels as RF overlay wavelengths over their PON (see Figure 5.9) to maintain that service for historical end users. However, cable operators are transiting away from RF TV channels to IPTV and OTT content as these are more efficient technologies and enable cable operators to provide the service outside their network. Therefore, in the context ODN sharing, it seems unlikely that cable operators will provide RF TV channels for new end users who are used to IPTV and OTT content.

However, we believe that, in order to extend its RFoG footprint, the cable operator may purchase duct access wholesale products from the incumbent operator (wherever they are available and map onto its own network topology) to reduce deployment capex.

71 We anticipate that a 2.5Gbit/s-capable ONT will be 20% to 25% more expensive than the current 1Gbit/s ONT.

5.5 Active ODN sharing (Layer 2 VUA and Bitstream)

Description

Layer 2 VUA and Bitstream products are probably the most popular wholesale products in Western Europe for FTTH networks. They provide an active circuit between two demarcation points.

- *VUA*

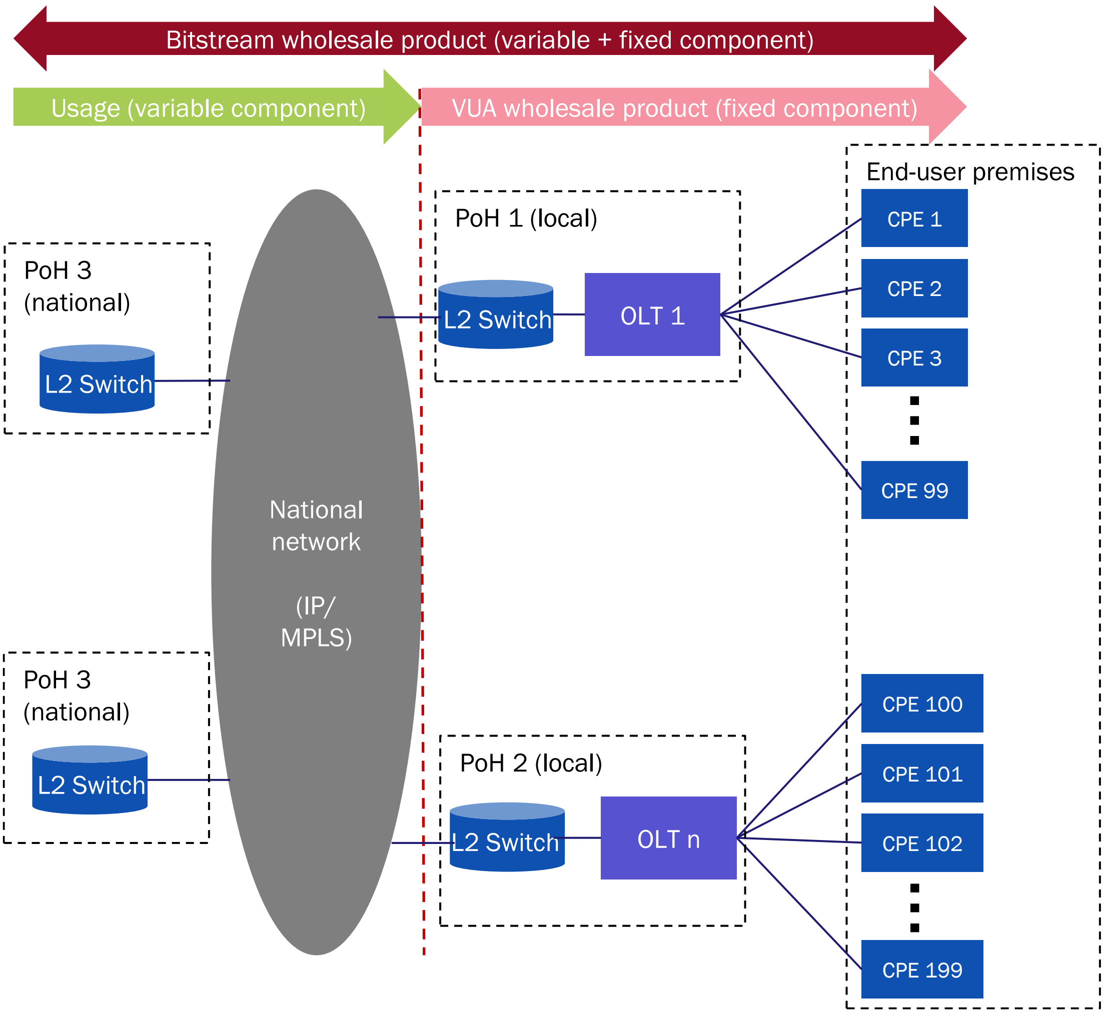
The typical demarcation point for the VUA service is between the handover switch at the OLT site and the customer-facing LAN port on the ONT located at customer premises. VUA only allows access seekers to provide broadband services to end users which are within the footprint of the ODN network covered by that OLT location. In Figure 5.10, it can be seen that points of handover (PoH) 1 and 2 are local PoHs for access seekers to interconnect to VUA wholesale products. If an access seeker interconnects through the switch located in PoH 1, it will only be able to deliver wholesale services to end users 1 to 99. However, if the access seeker interconnects through the switch located in PoH 2, it will only be able to deliver wholesale services to end users 100 to 199.

- *Bitstream*

In marked contrast, Bitstream usually enables access seekers to provide broadband services from a single PoH to the entire footprint covered by the wholesaler's ODN. This is usually achieved through an MPLS[72] network which acts as backhaul to connect all OLT locations nationwide. The backhaul service provided by the MPLS network is referred to as the "usage" part of the service in Ireland. This is because the price of this service is usually a function of the total bandwidth rented by the access seeker to the wholesaler on the IP/MPLS network. Figure 5.10 illustrates the VUA and Bitstream wholesale product concepts. If an access seeker interconnects through the switch located in either PoH 3 or PoH 4, it will be able to provide broadband services to all end users. However, in order to do this, it will need to purchase some bandwidth (i.e. usage) in the backhaul network as well as fixed VUA wholesale products. The combination of the usage part and the VUA is known as Bitstream wholesale product.

72 Multi-protocol label switching.

Figure 5.10: VUA and Bitstream concepts [Source: Analysys Mason, 2022]



Operational and commercial limitations

When using Bitstream and VUA wholesale products, access seekers are highly dependent upon the characteristics of the wholesaler's products. For example, if the wholesaler only offers wholesale products with download speeds of 1Gbit/s, 500Mbit/s and 250Mbit/s respectively, there is limited scope for access seekers to differentiate. The wholesale service portfolio that can be offered by wholesale operators is effectively limited by the following key components:

- xPON technology used (i.e. GPON vs XGS-PON)
- type of ONT used (i.e. 1Gbit/s ONTs vs. 2.5 Gbit/s ONTs)
- wholesale network design choices such as split ratio.

The bandwidth of the wholesale service provided is not only constrained by the xPON technology used (i.e. GPON vs. XGS-PON) but also by the type of ONTs the wholesaler installs at end-user premises. For example, wholesalers that have deployed XGS-PON technology usually do not currently provide wholesale services in excess of 1Gbit/s, which is similar to wholesalers that have only deployed GPON. This is because they have selected cost-effective ONTs with a 1Gbit/s throughput. ONTs with higher throughput are available from equipment vendors (e.g. ONT with a 2.5Gbit/s throughput) but are 20% to 25% more expensive than standard 1Gbit/s ONTs and 1Gbit/s services seem to meet market demand currently.

Finally, the wholesale service is also limited by the network design and engineering rules used by the wholesale provider. For example, different wholesalers may use different splitting ratios meaning that the same capacity may be shared by more end users, resulting in increased likelihood of congestion during peak time. Also, different wholesalers will have different rules to allocate top tier speed users on different PONs to ensure that there are not too many heavy end users on a particular PON that would hog the bandwidth.

As a result, access seekers can only differentiate themselves in terms of how they provision capacity in their own network (i.e. by how much internet capacity they provision for each user), which significantly affects end users' experience of the service, especially during busy periods (i.e. in the evening when residential subscribers mostly use their broadband service).

5.6 Network slicing (SDN and NFV/FANs)

Description

SDN and NFV currently have a limited footprint in commercial networks but interest in the virtualisation of networks through network slicing is on the rise. As explained in the previous section, VUA and Bitstream offer limited scope for innovation and competition due to the fixed nature of the wholesale products offered by the wholesaler and are dependent on the characteristics of the wholesaler's network.

SDN/NFV-enabled networks allow for the partition a wholesaler's network, making it easier to create slices in the network with defined boundaries. This means multiple access seekers are able to be more innovative, providing differentiated services to end users (for example using the FANS architecture described in Section 3.3.5), fostering creativity and competition even within a single wholesaler's network.

Considering FANS has been defined since 2017, there has not been much adoption. To date, only one FANS trial has been publicly announced by Nokia in 2019 with Lebanon's fixed network services provider Ogero. One trial has been publicly announced to date. The aim was to demonstrate how an infrastructure provider could use network slicing to provide wholesale services to access seekers.[73] However, no further information on the trial was released, or on whether the FANS technology has been commercially adopted by Ogero.

73 https://www.nokia.com/about-us/news/releases/2019/06/04/ogero-trials-nokia-fixed-access-network-slicing-virtualization-solution-to-enhance-its-wholesale-capabilities/

Operational and commercial limitations

Network slicing relies on NFV and SDN technologies, which have been part of WAN/IT for nearly a decade, and has been implemented in 5G core networks since the technology started to be deployed. However, SDN/NFV is a relatively newer concept in fixed telecoms networks and, as a result, wholesale operators seem hesitant to adopt this technology in the context of ODN sharing, as giving control to access seekers to a virtual "slice" of their physical network represents a significant paradigm shift compared with fixed VUA/Bitstream wholesale products.

A key element for the success of network slicing will be the complexity to integrate the access seeker and the network infrastructure provider's SDN layers to allow the access seeker to control its own network slice. The standardisation of APIs through the Broadband Forum FANS specifications will be useful in alleviating this challenge but we believe that, especially for small access seekers, integration will be challenging and as a result, we do not believe that this technology will be adopted in the context of ODN sharing before the mid-to-late 2020s.

6 Conclusions

In this section, we provide a summary of all ODN sharing mechanisms presented in this report and assess their respective technical feasibility as well as their operational and commercial limitations.

We believe that the following ODN sharing mechanisms have some potential:

- Despite the limitations introduced by the high dependency on the wholesaler's product portfolio and wholesale network design, **Layer 2 VUA and Bitstream** wholesale products have been popular in many countries and will continue to be offered by wholesalers for the foreseeable future as wholesale networks can be upgraded with next-generation PON technology (i.e. 25G-PON and/or 50G-PON).

- **Wavelength overlay** has the potential to be one of the toolkits for access seekers to serve large and medium enterprises as well as 5G backhaul using ODN sharing, although the solution will only be commercially available in the next 12 months. We also note that wavelength overlay has some potential for access seekers to target densely populated residential areas by installing a multiport switch in a cabinet or in the basement of an MDU building for instance and extend connection to end users from that switch. However, the success of the wavelength overlay model will depend on how the wavelengths can be standardised.

- **SDN/NFV network slicing** is still a nascent technology in fixed access networks but has the potential to overcome the limitations associated with Layer 2 VUA and Bitstream as it will allow access seekers to create their own services on the wholesaler's network, helping them to be innovative and differentiate themselves. However, wholesalers are not ready to allow access seekers to control part of their networks as it represents a significant paradigm shift compared to VUA/Bitstream wholesale products. As a result, we do not believe that this technology will be adopted in the context of ODN sharing before the mid-to-late 2020s.

However, we believe that the following ODN sharing mechanisms may be more challenging to implement:

- The **PON wavelength sharing model** has too many operational and commercial limitations to be adopted anywhere as it would only allow a single operator on the ODN, would prevent the wholesaler from deploying the same technology as the access seeker and, if the access seeker decides to deploy 50G-PON, the wholesaler would need to disable either its GPON or XGS-PON network.

- The **passive sharing (dark fibre) model** has been widely adopted in rural France but is unlikely to meet the same success in Ireland as the government has already devised and implemented the NBP for the Intervention area in rural Ireland where the main wholesale products are VUA and Bitstream and is too expensive due to the addition of a large cabinet to manage the connections to be used in commercial areas.

- **RFoG ODN sharing** is technically possible as RFoG wavelengths are different from xPON standardised wavelengths but is unlikely to be selected by cable operators due to the potential topology misalignment between cable network and the ODN in terms of equipment location, the fact that XGS-PON-based wholesale service has the potential to provide superior broadband services to DOCSIS 3.1, and the fact that cable operators are gradually replacing their RF TV channels with IPTV and OTT content, which means that sharing the ODN just for RF TV channels is not futureproof or economically viable.

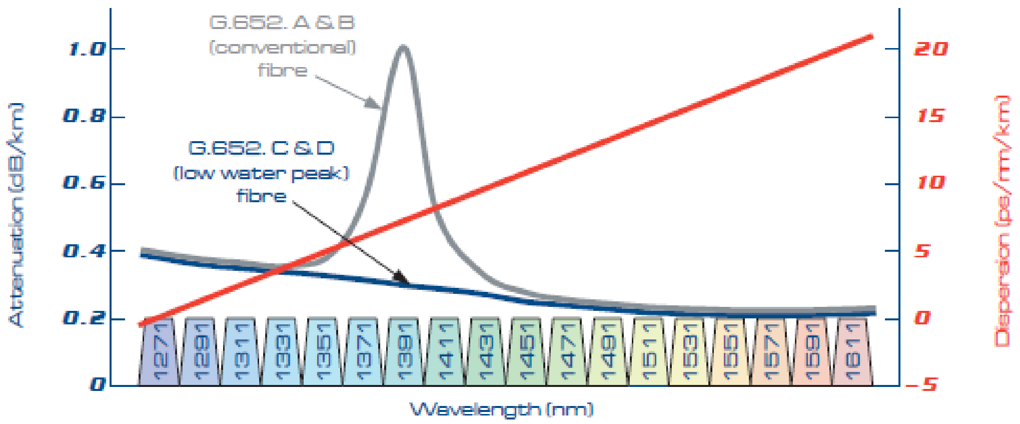
Annex A WDM concept

WDM is a process which allows several signals on different wavelengths to be transmitted in the same fibre, thereby increasing the bandwidth which can be carried in a single fibre. This concept allows the transmission of different PON technologies on the same fibre. WDM systems are classified into two groups based on the spacing of the wavelengths multiplexed:

- **coarse WDM** (CWDM) systems, which typically support fewer than 18 multiplexed wavelengths per fibre
- **dense WDM** (DWDM) systems, which typically support more than 32 multiplexed wavelengths per fibre and up to 320 wavelengths per fibre in long-haul applications.

CWDM systems are generally less sophisticated (and hence less expensive) than DWDM. The ITU has developed a 20nm channel spacing grid for CWDM, as specified in G.694.2, using signal wavelengths between 1271nm and 1611nm. This is illustrated in Figure A.1. The resulting CWDM can support up to 18 (typically 16) channels per fibre. The large channel spacing was designed to establish a cost-efficient WDM framework able to accommodate less sophisticated (i.e. less expensive) lasers that have a high spectral width. CWDM is typically used in access networks.

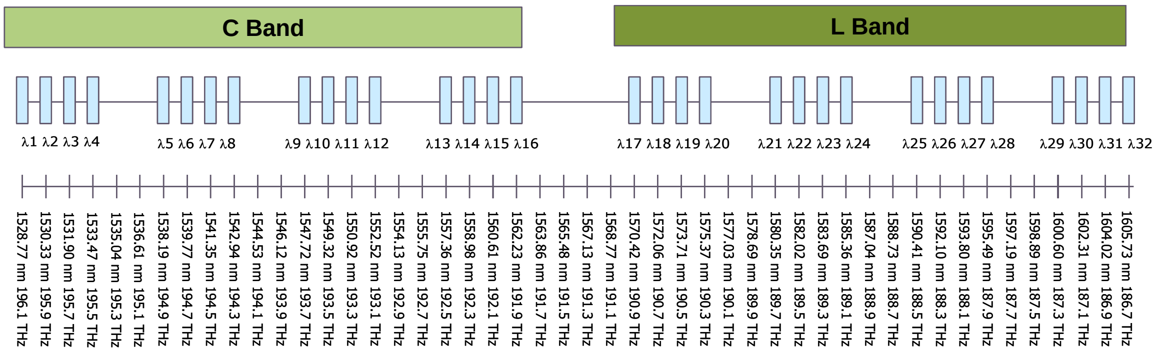
Figure A.1: ITU G.694.2: 20nm CWDM grid [Source: ITU]



We note that the upstream wavelengths in xPONs are defined with a spectrum of 20nm or larger meaning that they are CWDM transmitters. This is because upstream wavelengths are the wavelengths transmitted by the end-user ONT and it is crucial to keep the end-user CPE cost down for the success of the technology.

DWDM tends to be used at a higher level in the network infrastructure due to its greater capacity. The ITU has specified a frequency grid for DWDM systems which consists of 0.8nm (100GHz) channel spacing, in standard ITU G.692. For practical purposes the grid has been extended to provide 50GHz (0.4nm) and 25GHz (0.2nm) spacing. Today, some commercial DWDM systems can provide up to 160 wavelengths in the C-band and an additional 160 wavelengths in the L-band. An example of a 32-wavelength system using the 100GHz grid is illustrated in Figure A.2.

Figure A.2: ITU 100GHz DWDM grid [Source: Analysys Mason, 2022]



DWDM systems operate exclusively within the C- and L-bands.[74] Because of the smaller channel spacing, laser transmitters used in DWDM systems need to be significantly more stable than those used in CWDM systems. They must also be designed with precise temperature control to prevent drift from the very narrow centre wavelength. The higher cost of using such lasers is a major factor in the higher cost of implementing DWDM systems.

74 The ITU wavelength grid is also defined for the S-band but due to the lack of optical amplifiers operating in this band, DWDM equipment vendors do not use the S-band.

Annex B List of contributors to this report

We would like to thank all the contributors to this report, who generously assisted us by offering their technical expertise:

- **Ana Pesovic** (Marketing director, Nokia)
- **Cornel Ciocirlan** (CTO, Commscope)
- **Ignacio Garcia Comin** (Director of Strategy EMEA, Commscope)
- **Musia Yu** (Analyst Relations, Optical Business Product Line, Huawei)
- **Ronan Kelly** (EMEA CTO, ADTRAN)

Annex C Glossary of terms

The acronyms given here are those used in this report.

Figure C.1: List of acronyms used in the report [Source: Analysys Mason, 2022]

Acronym	Definition
AAA	Authentication, authorisation and accounting
API	Application programming interface
AR	Augmented reality
BNG	Broadband network gateway
BSS	Business support system
BT	British Telecom
CE	Co-existence element
CMTS	Cable modem termination system
ComReg	Commission for Communications Regulation
CPE	Customer premises equipment
CWDM	Coarse wavelength division multiplexing
dB	Decibel
DL	Downlink
DOCSIS	Data over cable service interface specification
DP	Distribution point
DPU	Distribution point unit
DSP	Digital signal processing
DWDM	Dense wavelength division multiplexing
ECNDP	European Climate Neutral Data Centre Pact
EFM	Ethernet in the first mile
Emta	Embedded multimedia terminal adapter
EPON	Ethernet passive optical network
ESA	Exchange serving area
EVC	Ethernet virtual connection
FANS	Fibre access network sharing
FEC	Forward error correction
FSAN	Full-service access network
FOAS	Future optical access system
FTTP	Fibre to the premises
FTTx	Fibre to the x
FWA	Fixed-wireless access
Gbit/s	Gigabits per second
GS-PON	Gigabit symmetric passive optical network
GPON	Gigabit PON

Acronym	Definition
HD	High definition
HFC	Hybrid fibre coaxial
IEEE	Institute of Electrical and Electronics Engineers
INEA	Innovation and Networks Executive Agency
IP	Internet protocol
IPTV	Internet protocol television
ISP	Internet service provider
ITU	International Telecommunications Union
ITU-T	ITU Standardisation
KDDI	Japanese telecoms operator
L0	Layer 0
L1	Layer 1
L2	Layer 2
L3	Layer 3
LAN	Local area network
MAC	Medium access control
Mbit/s	Megabits per second
MDU	Multi-dwelling unit
MPLS	Multi-protocol label switching
MSA	Multi-source agreement
MUX	Multiplexer
NBI	National Broadband Ireland
NBP	National Broadband Plan
nbn	Australia's National broadband network
NFV	Network functions virtualisation
NG-PON	Next-generation passive optical network
NIU	Network interface unit
nm	Nanometre
NOC	Network operations centre
ODN	Optical distribution network
ODP	Optical distribution point
OLT	Optical line terminal
ONT	Optical network terminal
OSI	Open systems interconnection
OSS	Operations support system
PC	Personal computer
PIN	Public initiative network
PoH	Point of handover
PON	Passive optical network
PtP	Point to point

Acronym	Definition
QoS	Quality of service
RGW	Residential gateway
RF	Radio frequency
RFoG	Radio frequency over glass
RSP	Retail service provider
SD	Standard definition
SDAN	Software-defined access network
SDN	Software-defined networking
TD	Time division
TDM-PON	Time division multiplexing PON
TDM	Time division multiplexing
TWDM-PON	Time wavelength division multiplexing passive optical network
UHD	Ultra-high definition
VNF	Virtual network functions
VR	Virtual reality
VUA	Virtual unbundled access
WDM-PON	Wavelength division multiplexing passive optical network
WDM	Wavelength division multiplexing
XG-PON	10G PON