The Path Not Traveled

An Analysis of Modern PON Technologies in the Evolutionary Path of HFC Networks

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1. Introduction

While predictions of the rate of internet traffic growth might vary, broadband service providers are clear that their networks need to evolve to support higher capacities and new distinguishing features. Charting a network's evolutionary path is always a challenge and today's glut of technology options brings a heightened awareness of the potential for "regrettable spend".

Broadband service providers are charting an evolutionary path for their existing Fiber-to-the-Premises (FTTP) architectures and for their Hybrid Fiber-Coaxial (HFC) networks. The plethora of options for Passive Optical Network (PON) clouds the decision-making process.

The present text will provide a comparative analysis of 10G PON, 25G PON, 50G PON, and 100G Coherent PON technologies, summarizing their technical merits, deployment scenarios, and economic considerations. The paper will briefly survey the various models of internet usage and highlight how each technology can address escalating bandwidth requirements. It will overview the specifications, capabilities, and potential use cases for each PON technology. The paper is designed to be an introductory framework which can be used to help select the most appropriate PON technology, tailored to the specific needs of new deployments and the upgrade paths for existing networks.

2. Trends in Broadband Usage

The industry literature is littered with bandwidth usage reports, trends of billboard rates, and projections for future internet bandwidth demand.

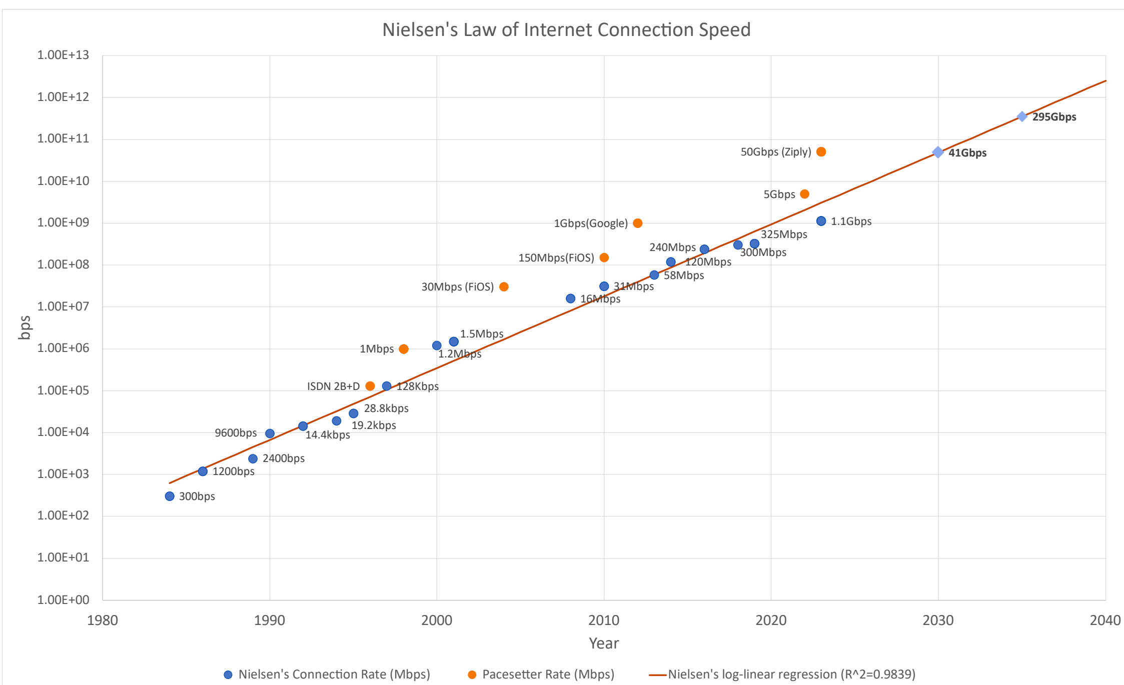

Figure 1 - Nielsen's Law of Internet Connection Speed

Probably the most well-known record of internet access speeds is Nielsen's Law of Internet Bandwidth (Nielsen, 2023). Nielsen has tracked his own internet connection speed over a period of 30 years and has observed that his connection speed follows a 50% per-year increase. This trend is plotted in Figure 1. Also shown on Figure 1 is the history of highest advertised speed available in the US market (pacesetters). Many have based their future projections on Nielsen's Law and have generally been close. Following Nielsen's projection would require service providers to deploy 50Gbps access networks by 2030 and 300Gbps access networks by 2035.

Cisco Systems' Annual Internet Report for 2018-2023 (Cisco, 2020) predicted a 20% CAGR in fixed broadband *average* connection speeds in North America.

Nielsen's law attempts to predict the "high-end" user's *connection speed*. Connection speed does not reflect the reality of how a user actually uses their connection. It is well understood that users do not demand the full data rate of their connection constantly or even on a regular or occasional basis. Numerous studies and models have shown that actual demand from a user during the busy hour might be in the few megabits per second when averaged over short periods of time and is bursty within those sample periods.

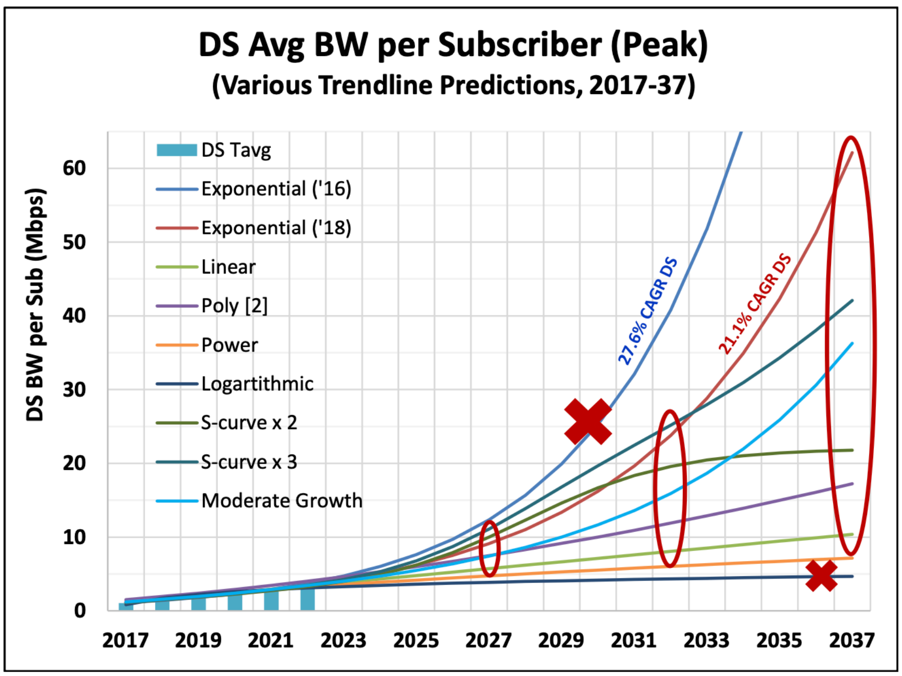

Figure 2 - Downstream Growth Projections (Ulm, Maricevic, & Ranganathan, 2022)

Other studies focus on actual usage. In the cable industry the most cited resource is a series of papers by Cloonan et al. The latest version (Ulm, Maricevic, & Ranganathan, 2022), by Ulm et al (Cloonan has since retired), studies access network usage data collected from a real-world network in the post-COVID19 era and uses that data to further validate the capacity modeling equations postulated previously. The authors observe that the growth of downstream *average* traffic usage began to slow in 2018 and was at 21% CAGR in 2022 whereas the previous growth rate was around 43%.

The conclusion in (Ulm, Maricevic, & Ranganathan, 2022) includes the chart in Figure 2. The authors project that downstream capacity requirements will be between 5Mbps and 22Mbps per subscriber by 2030 and between 7Mbps and 47Mbps per subscriber by 2035. While the study was focused on DOCSIS® networks, the projections should apply equally to PON and would claim that the peak required capacity on a 1:64 PON split would be just over 1.4Gbps by 2030 and 3Gbps by 2035. The study in (Ulm, Maricevic, & Ranganathan, 2022) did not anticipate 25Gbps PON being deployed in the market, nor the common place offering of 5Gbps symmetric tiers (and higher) in the competitive market by 2023.

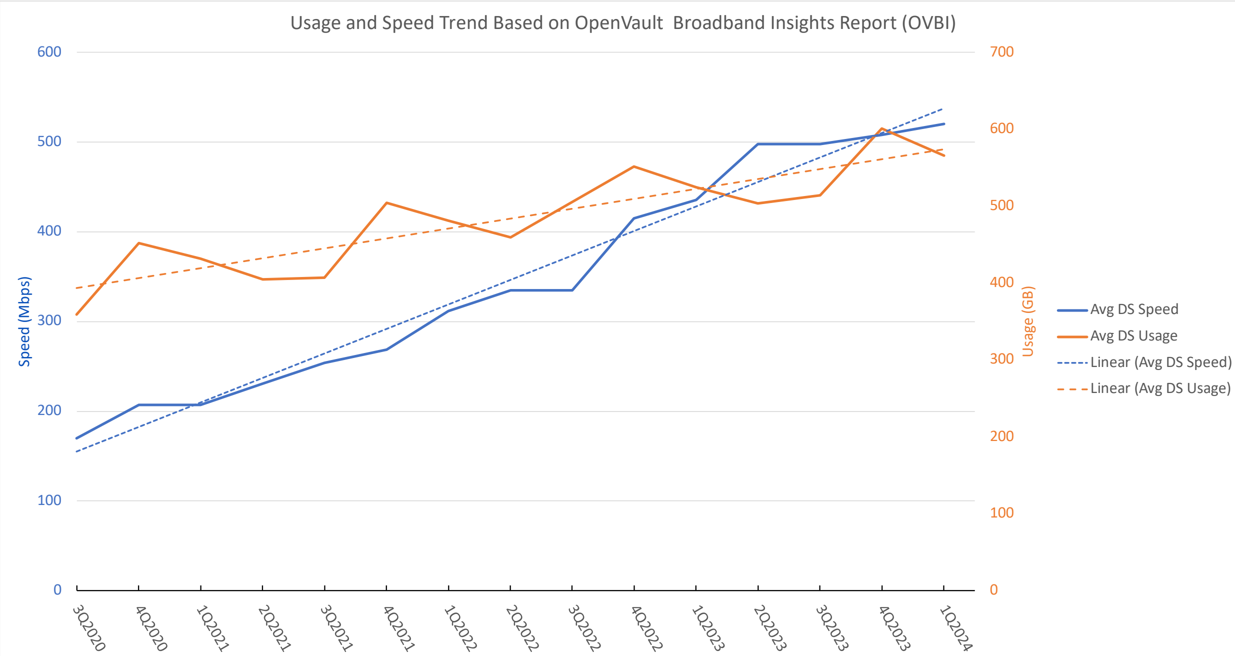

Figure 3- Usage Trends based on OpenVault OVBI Report 3Q2020 – 1Q2024 (OVBI, n.d.)

Finally, OpenVault's Broadband Insights report reports average upstream and downstream speeds and usage on a quarterly basis. A chart of the OVBI data from 3Q2020 through 1Q2024 (OVBI, n.d.) is shown in Figure 3. The downstream *connection speed* trend computed on this period of OVBI's data is 70% annual growth (21% quarterly) while the downstream *usage* trend is about 32% annual growth.

The reader should readily see that there is general agreement among reports and models, but predicting the future demands on an operator's access network is difficult because the models and perspectives of the public reports vary widely. The key point, though, is that the operator will need to develop a model and train that model with historical data from their own network. The model will need to be supplemented with additional data to help inform the projections for future demand. Those data points will include, but not be limited to the behavior of future applications, potential disruptive events, competitive drivers, and more. This model will help establish the timeline for when a given access technology will no longer meet the operator's network capacity requirements.

3. The State of PON Standards and Technology

The FTTP industry is experiencing a boom. Worldwide there is a push to expand access to broadband, and governments are allocating public money to the effort with a preference for fiber-based access. Further, most legacy telcos have found themselves at the end of the life of their twisted pair networks and are overbuilding their own networks with fiber. As discussed previously, while growth of internet usage seems to be slowing, it has not plateaued. With these factors, PON is being deployed in new and sometimes unanticipated use cases. PON standards and technology are advancing to keep up with these new demands.

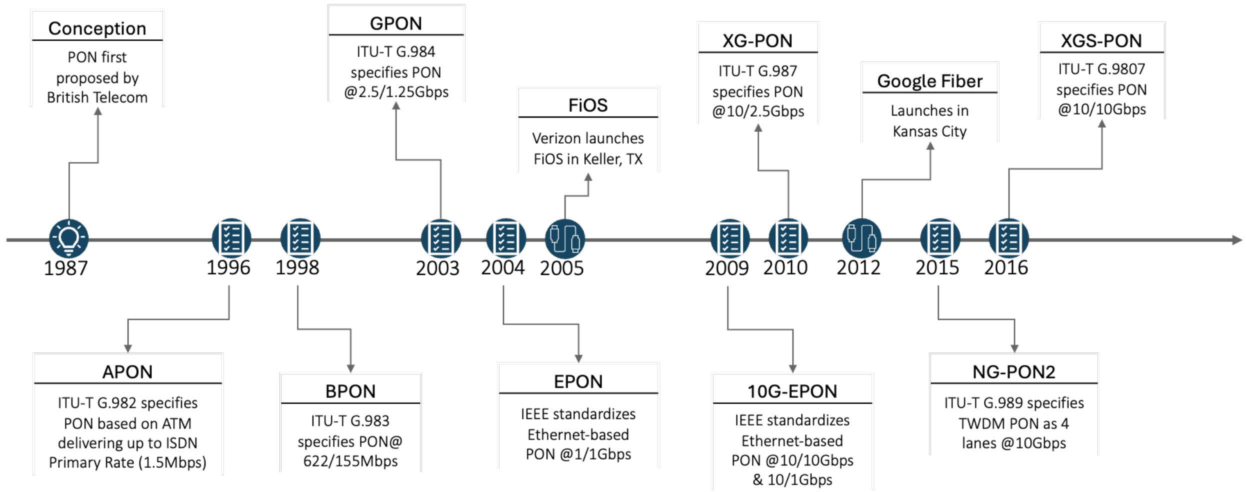

Figure 4 – A Quick History of Passive Optical Networks

The documented history of PON, summarized in Figure 4, begins in 1987 when engineers at British Telecom proposed and demonstrated the concept (Stern, et al., 1987). PON has appreciated a significant growth spurred by major events like the launch of Verizon FiOS in 2005 and Google Fiber in 2012. Today 10Gbps PON (10G-EPON and XGS-PON) is being deployed extensively in green-field scenarios, as a replacement to GPON and EPON, as a replacement for DSL and, in a growing number of cases, as an overbuild of HFC networks.

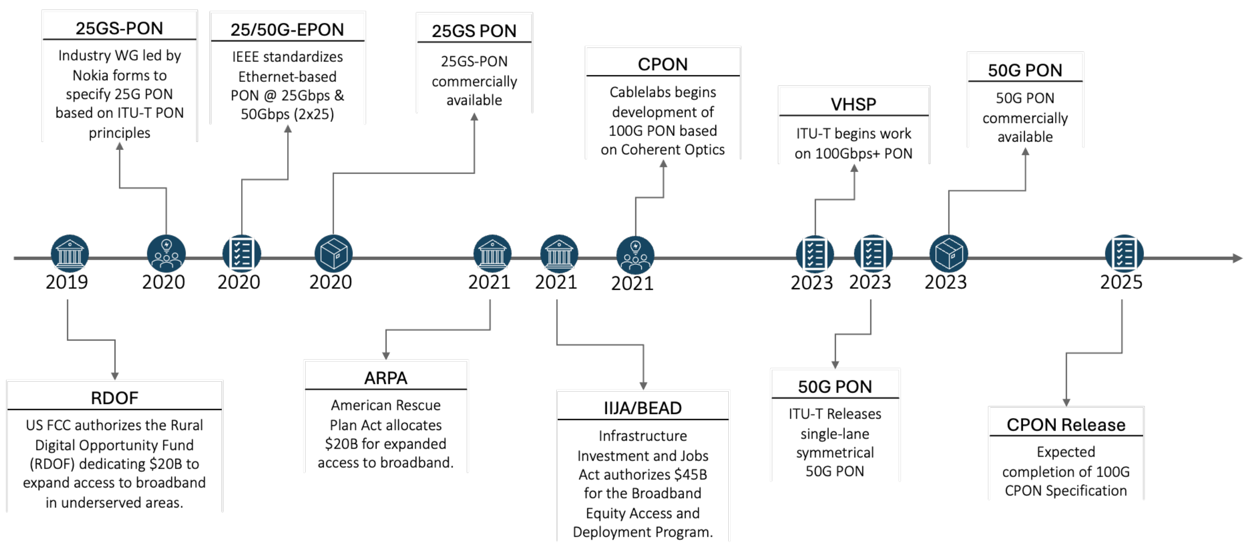

Figure 5 - The Future of PON and its Key Drivers

The modern timeline for PON, shown in Figure 5, and the future of PON is being driven by a unique convergence of factors. The most often referenced driver for advancements in PON is the growth of demand for higher access speeds and raw consumption of data. As discussed earlier, projections estimate that a 40Gbps connection speed might be required for high-end users by the year 2030, but actual average usage supports a much lower required capacity. Of more interest currently is the worldwide push to deliver internet access to those populations that are underserved. For example, in the United States since 2019 over $80 billion of public money has been allocated to this purpose through the Rural Development Opportunity Fund (RDOF) and Broadband Equity, Access and Deployment (BEAD) programs. FTTP is favored by policy makers. Because many of these areas are remote, PON is being pushed to go further distances. Demand in more populated areas drives a need for PON to achieve higher split ratios and deliver higher capacity.

3.1. 10Gbps PON

10Gbps PON was introduced to the market in 2009 by IEEE 802.3 as 10G-EPON. ITU-T quickly followed with XG-PON, which is asymmetric, and XGS-PON in 2016 which delivers symmetrical data rates.

3.1.1. 10G-EPON

EPON is the predecessor to 10G-EPON and, until the mid 2010s, was the most widely deployed version of PON worldwide. Several North American cable operators deployed EPON in support of FTTP and mobile backhaul beginning in the mid 2000s. 10G-EPON products became available as early as 2010.

CableLabs included support for 10G-EPON in the DPoE 1.0 specification which was released in 2011. Not desiring to adopt the previous generation of PON technology and encouraged by DPoE support from several suppliers, notably Sumitomo and Alcatel-Lucent, major cable operators quickly adopted 10G-EPON as the strategic path for FTTP deployments. Deployments of 10G-EPON in the Time Warner Cable network began as early as 2014 under guidance from the authors. Today, 10G-EPON is not widely adopted beyond the cable industry and is currently a small and slowly shrinking share of the PON equipment market (see Figure 6).

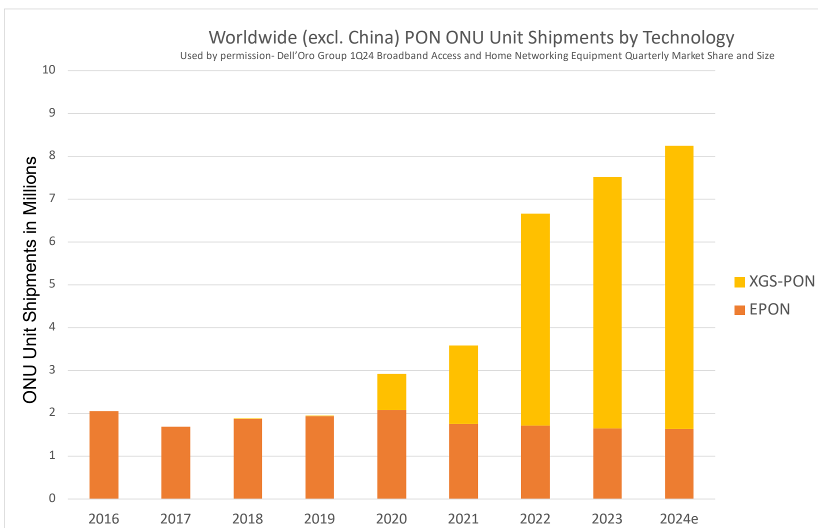

Figure 6 - XGS-PON vs. 10G-EPON ONU Shipments (Used by permission - Dell'Oro Group 1Q24 Broadband Access and Home Networking Equipment Quarterly Market Share and Size; Ulm, Maricevic, & Ranganathan, 2022)

The advantage that a cable operator will find in choosing 10G-EPON is the common availability of OLTs and ONUs that conform to the DOCSIS Provisioning of EPON (DPoE) series of specifications from CableLabs. The DPoE suite of specifications accomplished two very important things for 10G-EPON and the cable industry. DPoE created a method by which a cable operator can integrate PON into their back-office systems using DOCSIS-style provisioning and management protocols – in essence making the PON network appear as a DOCSIS network to the back-office. The second achievement for DPoE was to create a very well refined interoperability scheme, and accompanying certification program, that enables an ONU from any vendor to interop with an OLT from any other vendor.

3.1.2. XGS-PON

GPON, the predecessor to XGS-PON, gained traction in the market when Verizon began deploying it in its FiOS network in the early 2000s. Anecdotal evidence suggests some cable operators were deploying GPON as early as 2004. GPON continues to enjoy wide support by the legacy telcos. However, XGS-PON emerged in 2020 as telcos and "neo-ISP" operators, looking strategically forward, chose to deploy 10Gbps PON. XGS-PON is well down the path of becoming the dominant PON standard for the next 5 years.

PON based on recommendations issued by ITU-T has a reputation for poor interoperability. This reputation is well deserved, but interoperability is improving under Broadband Forum's BBF.247 certification program and other efforts across the industry like the VOLTHA (Open Networking Foundation , n.d.) project and CableLabs' Common Provisioning and Management of PON (CPMP) working group.

Today, comparing the cost of 10G-EPON products to the cost of XGS-PON products, the analyst will find little difference. As a result, a cable operator's choice of 10G-EPON vs. XGS-PON is going to be driven by (a) the operator's legacy network architecture; (b) the level of effort to integrate the chosen implementation into the backend; (c) interoperability of the chosen OLT and ONUs. The decision will not be dominated by the equipment cost.

It should be noted that while there are many suppliers of 10Gbps PON OLT and ONU systems. Manufacturers such as Cortina, Ciena, MicroSemi, MaxLinear, and SemTech supply PON application specific integrated circuits (ASIC), but the supply of PON ASICs is dominated by Broadcom. It should also be noted that virtually all available 10Gbps PON ASICs support 10G-EPON and XGS-PON in the same component. This factor is significant in explaining the lost cost difference between 10G-EPON and XGS-PON.

Table 1 provides the reader with a summary of the key factors that might influence an operator's choice of which PON type to select and deploy today.

Table 1 - Summary Comparison of Modern PON Products

	10G-EPON	XGS-PON	25GS-PON	50G-PON
Max Usable Capacity (DS/US)	~10Gbps/8.8Gbps	~10Gbps/8.8Gbps	~25Gbps/21Gbps	--
Product Availability	Widely available	Widely available	Limited sources	Limited sources
Interoperability	Excellent under DPoE	Fair but improving under BBF.247	Poor due to limited sources	Poor due to limited sources
Relative ONU Cost	Comparable to XGS-PON	Comparable to 10G-EPON	High ONU cost relative to XGS-PON	Very high ONU cost relative to XGS-PON

Back Office Integration for Cable Operators	DPoE	Proprietary DPoX or proprietary APIs; open APIs slowly being introduced	proprietary APIs; open APIs slowly being introduced	proprietary APIs; open APIs slowly being introduced

3.1. 25Gbps PON

There are two specifications for 25Gbps PON. IEEE 802.3 issued a standard for 25G/50G PON (IEEE 802.3ca) 2020. The second, 25GS-PON, came to the industry under the 25GS PON MSA after much debate and ultimate rejection within the ITU-T to pursue development of a 25Gbps recommendation.

IEEE 802.3ca specifies two flavors of PON – 25G EPON and 50G EPON, which is simply two lanes of 25G EPON. 25G EPON builds on 10G EPON and adds new features that enable scalability beyond 50Gbps operation. In fact, the original goal of the IEEE 802.3ca project was to create a standard that would reach 100Gbps using four lanes of 25Gbps. Like all previous PON standards, 25G EPON uses intensity modulation with direct detection (IM-DD). In the case of 25Gbps, this allowed use of optical components that were already in the market, thus reducing the expected cost of an implementation.

The 25GS PON MSA is written as a "delta spec" – meaning that the MSA cites existing specifications as the basis and only specifies the changes necessary to enable a manufacturer to build a conformant product. The 25GS PON MSA cites IEEE 802.3ca as the basis of the physical medium dependent layer (PMD) and forward error correction (FEC). It cites ITU-T G.9807.1 for the TC layer and ITU-T G.988 for OMCI. In essence, 25GS PON is the 25Gbps equivalent of XGS-PON.

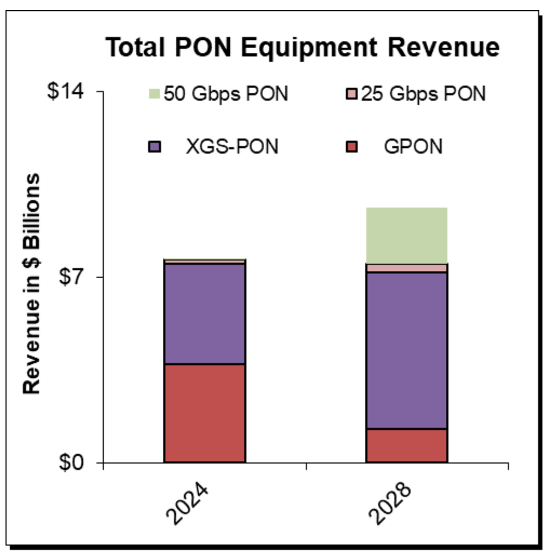

Figure 7 - Dell'Oro Projections for PON Equipment Revenue (Heynen, n.d.)

The market has not been kind for 25/50G-EPON. There is no known implementation of 25G-EPON or 50G-EPON on the market today.

Nokia released a 25GS PON OLT and ONU in 2020 soon after the MSA was completed. To date, little public evidence exists that other suppliers will enter the market, but there is substantial evidence in the rumor mill that several ONU suppliers and at least one other OLT supplier will enter the market in 2024.

This is supported by the announcement of a 25GS PON interoperability event to be held on behalf of Broadband Forum by CableLabs.

This planned interoperability event is also evidence that the industry is taking interoperability of future PON seriously. Broadband Forum, in particular, has a project underway to add 25GS PON into TR-309, TR-255, and TP-247 - the test plans that support interoperability in the ITU-T PON market.

Even though some analyst's predictions don't look positive for 25GS PON, as evidenced in Figure 7, there are valid reasons for an operator to consider 25GS PON for their strategy. This will be discussed later in the present paper.

3.1. 50Gbps PON

As mentioned previously, IEEE 802.3 released a standard for 50G-EPON in 2020, but it has failed to find any market traction. Some analysts are including 25/50G EPON in their forecasts which suggests that some product could come to market. With so much focus on 25GS PON and 50G PON from ITU-T at this time, it is difficult to see how a 25/50G EPON product could be competitive.

ITU-T began work on a 50G PON specification in 2019. The first release of 50G PON, in 2021, supported 50Gbps downstream and 10Gbps or 25Gbps operation in the upstream. The latest release, in 2023, adds support for 50Gbps operation in the upstream (ITU-T, 2023).

50G PON continues the tradition of using IM-DD, but to achieve the desired performance it is widely accepted that 50G PON requires a digital signal processor (DSP) and amplification, typically in the form of a semiconductor optical amplifier (SOA). These components are required in the ONU and add considerable cost to the device and to the overall system. In early analysis for IEEE 802.3ca, Liu et al (Liu & Tao, 2017) estimated that an ONU for 50Gbps single wavelength PON based on NRZ signaling and IM-DD would cost 1.2x the cost of a 25Gbps ONU. More recent estimates from Laubach et al (Laubach, Boyd, Harley, & Villarruel, 2024) put the cost closer to 3.3x that of a 25Gbps ONU.

It is difficult to find independent and publicly available estimates of this higher cost. Anecdotal predictions say the operator's actual cost to purchase a 50G PON ONU could be 10x the cost of XGS-PON and 25GS PON to be 6x the cost of XGS-PON. In their analysis and strategy development, operators are strongly advised to reference their favored data source such as Omdia or Dell'Oro as well as insights from CableLabs.

Costs, of course, will come down as operators begin to purchase more devices. This can only occur, though, if they are available. 50G PON is finding its way to the market. Several trials have been announced around the world including Huawei with Telecom Egypt (Telecom Egypt and Huawei join forces to complete the first 50G PON trial in Africa, 2024), PTCL (Pakistan conducts first Symmetric 50G-PON fibre-optic internet trial, 2024), and Saudi Telecom (stc) (stc and Huawei accomplish the first 50G PON live trial in the Middle East, 2023); Nokia with Google Fiber (Nokia and Google Fiber first in the U.S. to trial 50G PON speeds over live fiber broadband network, 2024); ZTE with Turk Telecom (Türk Telekom and ZTE conduct Europe-first 3-in-1 50G PON Combo trial in Türkiye, 2024) among others. Note that this sampling reflects a heavy leaning toward Chinese manufacturers which reflects strong support for 50G PON in China. Operators can expect other system suppliers to enter the 50G PON market as more PON ASIC choices become available, most likely from a traditionally dominant PON ASIC supplier.

The traditionally dominant PON ASIC supplier is notably missing from the 25GS PON MSA member list and has also made no press release or other public statement about coming support in its ASICs for 25G or 50G PON. Given the relatively dominant position in the market one might expect an ASIC supporting

50G PON to be released soon. Traditionally, the major PON ASICs have supported multiple generations of PON as well as multiple PON standards. With this view, it is easy to conclude that it is likely, but not guaranteed that said supplier will include support for 25G PON, whether 25G-EPON or 25GS PON, in an upcoming PON ASIC.

3.2. Beyond 50G PON

It might seem to be a stretch to consider access network capacity beyond 50Gbps, but operators would be missing the mark if they don't have this on their radar. In standards bodies there are projects to specify a next generation of PON that supports at least 100Gbps.

In ITU-T Q2/SG15, the work group that develops PON specifications within the ITU-T, work began in 2022 to understand the requirements and technology for a PON operating beyond 50Gbps. This document (G.sup.VHSP) is incomplete at this time. Much of the discussion about VHSP has been around whether to continue use of IM-DD technology (for example, NRZ and PAM4) or to transition to coherent optical transmission and whether the data rate target should be greater than 100Gbps (i.e. 200Gbps). Key issues in this realm are optical power and loss budget, desired reach and split ratios, impacts on receiver sensitivity, tunability, wavelength plans, and coexistence with earlier versions of PON.

G.sup.VHSP is expected to be completed in 2024. The reader should note that G.sup.VHSP, when published, is not a standard. It is a set of requirements that will guide development of the standard, which can be anticipated to take another 2 years to complete.

Beginning in 2021, CableLabs began work on 100Gbps PON based on coherent optics. The decision to abandon IM-DD is based around the nature of the cost and benefits of coherent optics.

Optical transmission based on coherent reception enables key changes in the optical link: high order complex modulation like PSK or QPSK; a new dimension of modulation using polarization; significant improvements in receiver sensitivity. These characteristics have made coherent optics a mainstay of long-haul, high-capacity links for nearly two decades, and implementations have continued to mature enabling smaller component designs, lower cost and lower energy consumption – all necessities for the access network.

Coherent optics, like 50G PON, require a DSP, but the SOA is not necessary. Therefore, it is further reasoned that the cost increment from 10G PON or 25G PON to 100G PON is similar to that for 50G PON. In other words, the cost difference between 50G PON and 100G Coherent PON should be small and the benefit (100Gbps) large.

These factors establish the foundation for CableLabs 100G CPON project. The project further intends to adapt to existing PON management and operational protocols like ITU-T G.9804.2, and ITU-T G.988. This strategy allows suppliers apply existing codebases to new CPON products and operators to reuse existing backend integrations developed for 10Gbps PON.

Also considered in the CableLabs CPON project and being discussed in ITU-T Q2/SG15 is the use of single carrier (SC) vs. digital subcarrier (DSC) techniques. Single carrier is the well understood method of modulating a laser at the full line rate with a single input signal that results in the familiar "single peak" spectral signature. DSC on the other hand is a technique that modulates the laser with multiple signals at some fraction of the full line rate and that results in a spectral signature with multiple peaks, in the output of a single laser.

While DSC is in scope for CableLabs' CPON project, single carrier is the current focus of the CableLabs working group. It is believed, given the state of technology and progress in standards, that a single carrier coherent PON product could be available on the market by 2030 or sooner. This prospect makes 100Gbps PON a realistic possibility in an operator's access network strategy.

Also of concern is development of multicarrier optical transmission like DSC. This approach has many potential advantages, and the technology to enable it is in the market. Namely, Infinera introduced its XR optical technology and created the Open XR Optics Forum (Open XR Optics Forum, n.d.) to further develop open specifications for this technology. Multicarrier transmission applied in a point-to-multipoint access network has the potential, by dedicating a carrier or subcarrier to each ONU, to remove concerns about media sharing and performance limitations associated with time domain multiplexing (TDM) that enable upstream transmission in PON today. Currently the cost, power consumption and size of these devices are the primary limiting factors for progress and adoption.

4. Integration Concerns

One of the key concerns for operators deploying PON, especially those that are deploying PON for the first time, is how to integrate the network elements into the back-office systems and to ensure interoperability between OLTs and ONUs. It is too easy to focus on the network architecture – PON OLTs, ONUs, outside plant design, etc – and minimize this aspect of the overall deployment. Customers today are shifting their concern from speed to reliability and seamless customer support experiences. Operators are feeling the competitive impact of this shift. It is impossible to deliver these experiences without including backend integration in the overall PON deployment strategy.

Backoffice integration includes functions like network element provisioning, service provisioning and activation, network monitoring, metric and fault analysis, billing, customer service, and more. While out of scope for this present paper to explain the many and varying functions in all layers of the network, Figure 8 illustrates how the interoperability and back-office integration are multilayered in the business and are not isolated to only one layer of the network itself.

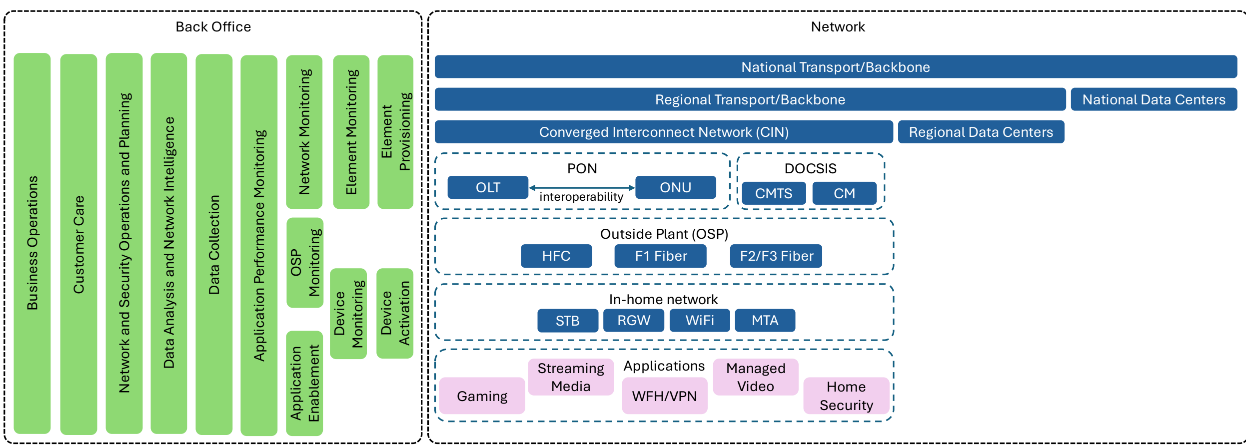

Figure 8 - The Many Layers of Network and Business Integration

Cable operators have long enjoyed the interoperability and back-office integration provided by DOCSIS through its standardized MAC layer protocols, provisioning interfaces and OSS interfaces. The DOCSIS methods and protocols are so well understood and integrated across multiple vendors' network equipment, billing systems, and network management frameworks that it is difficult to imagine changing that infrastructure. However, as an operator considers deploying PON in the network, this issue must be addressed.

PON systems do not natively support DOCSIS-style provisioning and operations. DPoE addressed this by specifying a framework through which DOCSIS methods could be adapted to support EPON and 10G-EPON. CableLabs' effort to duplicate this approach for GPON in the DPoG specifications has not gained traction in the market.

Historically, ITU-T PON implementations have a reputation for poor interoperability, especially for ONU management, and proprietary back-office integrations. Interoperability concerns are improving through efforts like Broadband Forum's BBF.247 ONU certification program and the TR-255 and TR-309 interoperability test plans. Broadband Forum is also tackling standardized management protocols and architectures to replace the proprietary back-office integrations. TR-383 defines a series of YANG data models that can be used to provision, manage, and monitor an ethernet-like access network. TR-385 extends TR-383 to support ITU-T PON types, including GPON, XGS-PON, NGPON2, and, more recently 25GS-PON and 50G PON. TR-413 is the beginning of an extensive series of TRs that define the "CloudCO" which is a framework for managing a broadband network through software-defined networking (SDN) and virtualized network functions (VNF) and using modern protocols like NETCONF, RESTCONF, gRPC, gNMI and others. The high-level architecture is shown in Figure 9. This architecture and derivative functions build on TR-383 and TR-385.

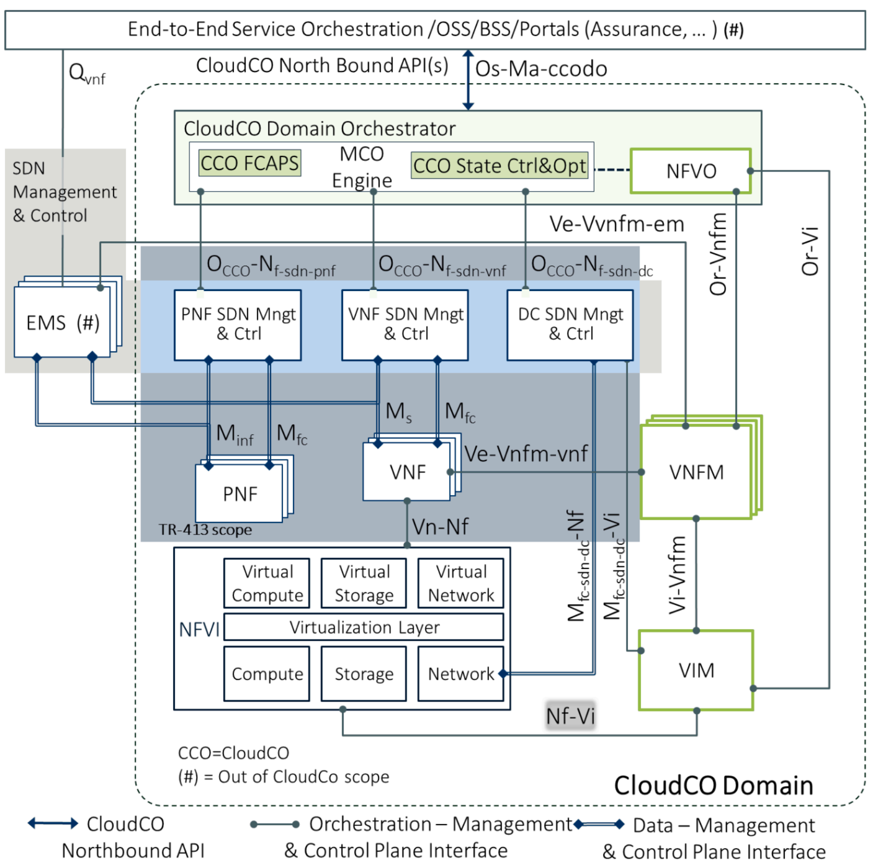

Figure 9 - Broadband Forum CloudCO Architecture (Broadband Forum, 2018)

It is beyond the scope of this present paper to explain this framework in detail and its potential applications in cable operator networks. However, when evaluating immediate needs and future directions for back-office integrations, operators should investigate Broadband Forum architectures combined with APIs defined by TMForum.

The operator must decide among several factors – time to market and cost of integration can be reduced by relying on DOCSIS-based provisioning (DPoE or proprietary DPoX implementations). However, reduced time to market be might gained at the expense of a reduced selection of vendors or increased reliance on a particular vendor (in the case of proprietary implementations). Selection of DOCSIS-based provisioning for PON might also be considered “kicking the can down the road” – in other words, a move to non-DOCSIS methods is inevitable. However, there might be a monetary expense and time-to-market penalty incurred when choosing to forgo DOCSIS provisioning in favor of quasi-proprietary interfaces or open interfaces like those from Broadband Forum.

5. Decision Making Framework

The operator must develop a decision-making framework that guides key decisions and is informed by all stakeholders across all business units within the organization. This includes business owners, the office of the CFO, network architects and engineers, network operations, field operations, construction and maintenance, customer care, billing, and more. Jacobson et al in (Jacobson, Noll, & Dang, 2016), describes a framework that can be adapted to the needs of the operator.

Within the present paper, we limit the scope of analysis to the key issues that might impact an operator’s choice of PON technology to deploy. These factors include but are not limited to:

- Desired time to market, which is often driven by competitive pressures
- Desired network capabilities and capacities (data rate, latency, split ratio, distances, etc.)
- Longevity of the chosen solution
- Ability to minimize the number of upgrades over time
- Initial capital cost and long-term operational cost
- Required scale in terms of product availability
- Level of effort for back-office integration
- Training and Field Operations/Logistics

6. Deployment and HFC Evolutionary Scenarios

Many operators are evaluating their strategy for PON deployments. Every operator’s situation is unique. Some are starting with old HFC networks that have not been maintained. Some have already deployed 10Gbps PON and are deciding whether to adopt 25GS PON or wait for 50G PON or even 100G PON.

We will consider three scenarios and explore the potential paths and decision points. Each scenario represents a different starting point for an operator’s network evolution.

6.1. Understanding the Timeline Charts

In each of the scenarios a chart is included. Each chart depicts the technology path(s) available for the given scenario. The horizontal axis of each chart represents time, but the time increments represent events rather than absolute points in time. The two event categories represented in the charts are “cost-effective” events and “requirement exceed” events. For example, “25G becomes cost effective” represents a point in time at which 25Gbps PON technology (e.g. 25GS PON) becomes economically feasible or justifiable for an operator. “Requirements exceed 10G” is the point in time at which 10Gbps PON technology (e.g. 10G EPON or XGS PON) can no longer meet the operator’s requirements and might be due to the demanded capacity or any other network performance metric (e.g. latency).

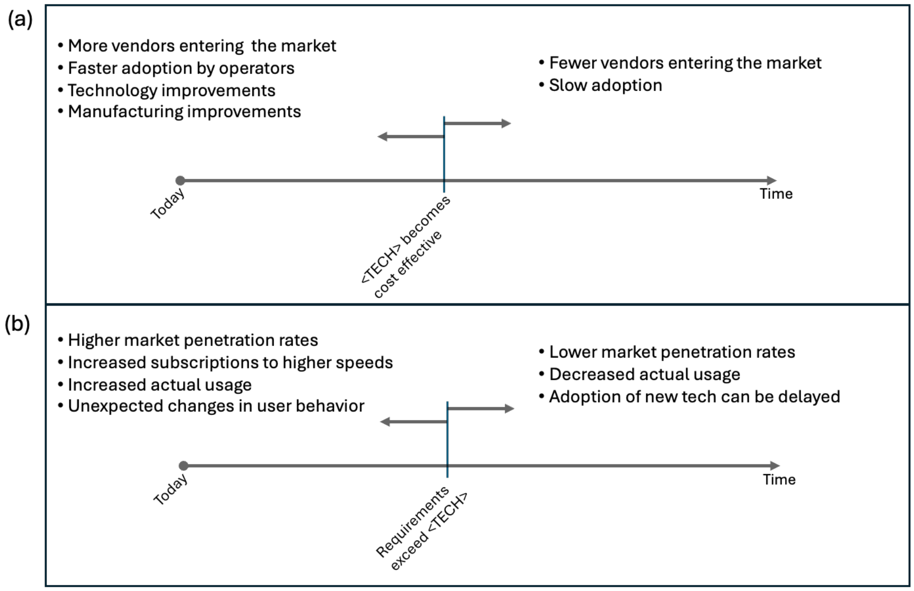

Figure 10 - Factors affecting timeline positions

Figure 10(a) lists examples of market factors that might affect the time at which a given technology becomes cost effective for the operator. Similarly, Figure 10(b) lists examples of market factors that might affect the time at which a given technology is no longer able to meet the operator's requirements to deliver the necessary products and to deliver them at an acceptable level of quality. Because each operator's business is unique, the position of each event depicted on the charts is determined by the operator's own analysis and modeling. The operator's analysis will move the individual events earlier or later in the timeline.

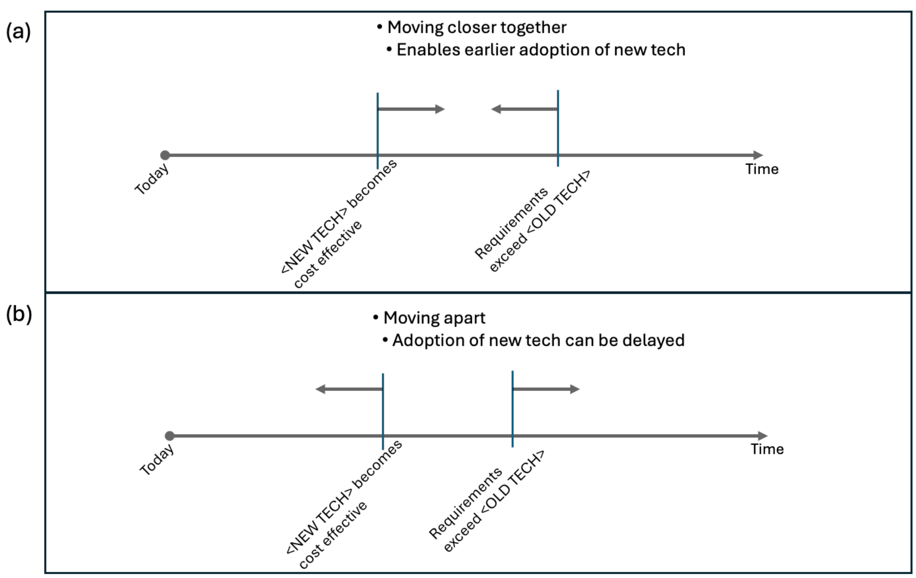

Figure 11 - Making sense of the gap between events

Movement of the individual events is important, but their position relative to one another and the width of the gap between each is the key to determining the progression of technology deployment within the operator's network. Figure 11 illustrates the more obvious movements that are possible.

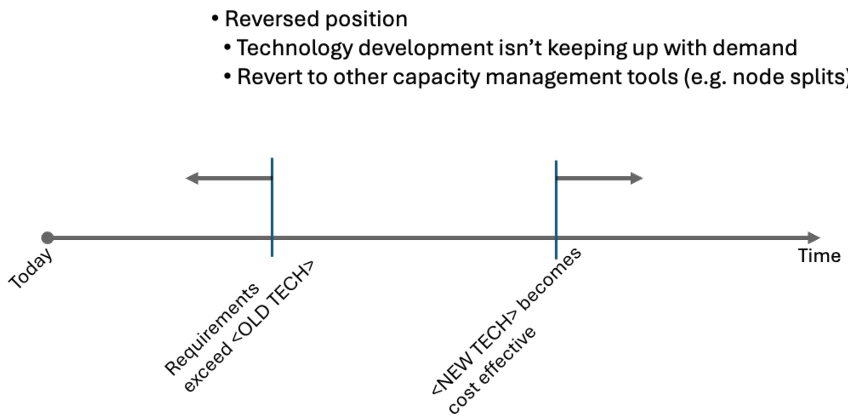

Figure 12 - Position reversal of key events

The analyst should be keenly aware that it is possible for a position reversal to occur as exemplified in Figure 12. In other words, the "cost effective" event for a new technology comes later than the "requirements exceed" event for the current technology. This would mean that the advancement of technology and/or the necessary cost reductions are not able to keep up with the advancement of consumers' increasing usage of the network or applications making demands of the network that cannot be met. In this situation the operator cannot rely simply on a technology upgrade but must resort to other methods to manage capacity or to reduce demand.

6.2. Scenario 1

Scenario 1 represents an operator that has determined that the cost of upgrading the HFC equals or exceeds the cost of deploying FTTP.

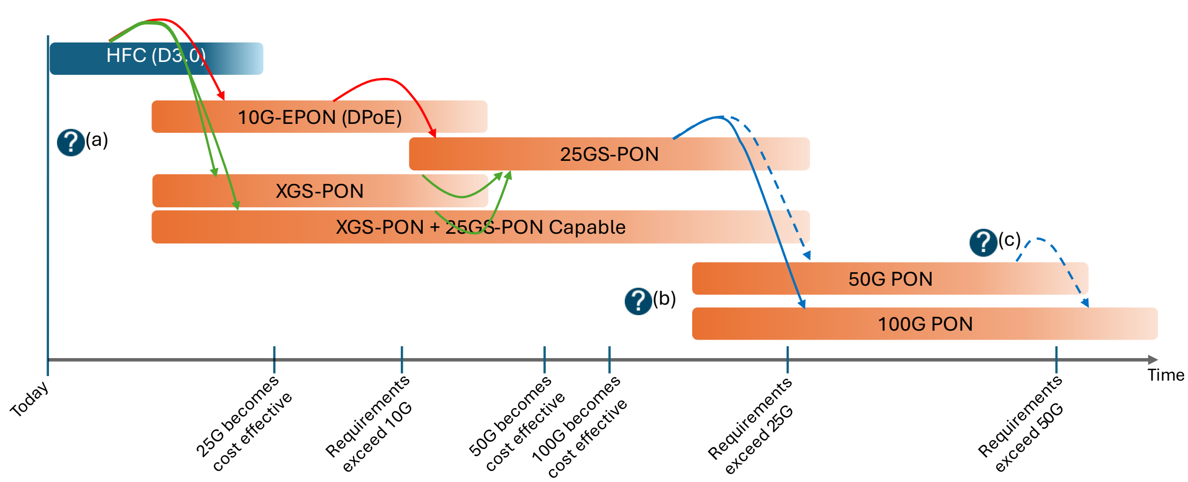

Figure 13 - PON Strategy for HFC that is to be decommissioned

Figure 13 depicts the various options available to the operator that is making this decision in the marketplace of 2024. The first decision point is item (a) in the timeline. In today's market 10Gbps PON is readily available, cost effective, and capable of meeting the demand of nearly all consumers and many businesses. The choice, then, is between 10G-EPON and XGS-PON. OLT products are available on the market that support XGS-PON and 25GS PON in the same PON port at a small premium in cost. This gives the operator an additional choice that might help avoid major equipment upgrades in the future.

Since each option is equivalent in all aspects of capacity and nearly equivalent in cost, the operator’s deciding factors among these will be:

- Time to market
- Longevity of the deployed product
- Level of Effort for back-office integration

10G-EPON with DPoE will easily be a lower level of effort to integrate into the cable operator’s back office and this will be the primary influence on time to market. However, it remains to be seen whether a 25G-EPON product will become available or whether it will gain any significant acceptance if a product does come to market. This means that a decision now to adopt ITU-T based PON might be warranted to avoid a disruptive transition later.

This makes XGS-PON a serious consideration even though the back-office integration might extend the time to deployment. Several suppliers are, though, developing and shipping proprietary DOCSIS-style provisioning systems for their ITU-T based PON products and this could lower the hurdles for deploying an XGS-PON solution sooner. Also to be considered is the need for this operator to construct the optical distribution network (ODN) to support PON. Construction and back-office integration could occur in parallel reducing the time-to-market concern.

If the connection speed projections discussed previously hold true for this operator, then by 2030 a 50Gbps PON might be needed. If this is true, then the operator might choose to deploy a product capable of only 10Gbps PON today and await arrival of cost-effective 50G PON products or even 100G PON products (decision point (b) and (c) in Figure 13). Given current cost projections out to 2030, neither 50G PON nor 100Gbps PON products will be competitively priced relative to 10Gbps PON products. This would be represented in the timeline as a shift toward the right of the “100G becomes cost effective” event. This could drive a coexistence strategy that allows “surgical” placement of 50G PON or 100Gbps PON to service specific customers while avoiding the cost of a wholesale upgrade.

6.3. Scenario 2

Scenario 2 represents an operator that will maintain the HFC network to support DOCSIS 3.0 or DOCSIS 3.1 and potentially continue upgrades to DOCSIS 4.0 and future generations of HFC technology. While the analysis of such a decision is of high interest, it has been analyzed throughout the literature and it is out of scope for this present text.

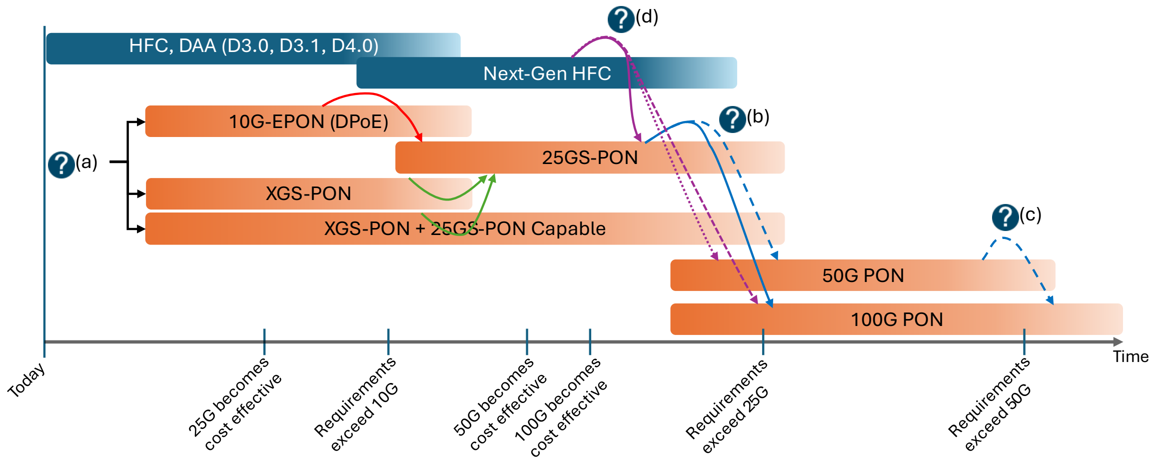

Figure 14 - Strategy for new PON that parallels continuous HFC upgrades

The operator in this scenario might decide to deploy FTTP due to competitive threats, requirements of grant funding, requirements of property owners (e.g. MDU owners), or a general strategy of building FTTP in all greenfield deployments.

The operator in scenario 2 might be less sensitive to time to market and more sensitive to the longevity of the chosen solution. As discussed previously, though, these factors are all unique to the operator. However, the key decision points, (a) (b) and (c) in Figure 14, and evaluation criteria are exactly the same as the operator in scenario 1. An additional factor in scenario 2 might be (should be) the eventual shift to overbuild the HFC network with FTTP, (d) in Figure 14.

In essence, scenario 1 and scenario 2 are variations on the same theme. Scenario 1 simply shifts decision point (d) to the present rather than sometime in the future.

6.4. Scenario 3

Scenario 3 represents an operator that has an existing deployed network of 10Gbps PON, whether 10G-EPON or XGS-PON. This operator might or might not choose to extend the life of their HFC network, but, as depicted in Figure 15, this scenario assumes an extended life of HFC.

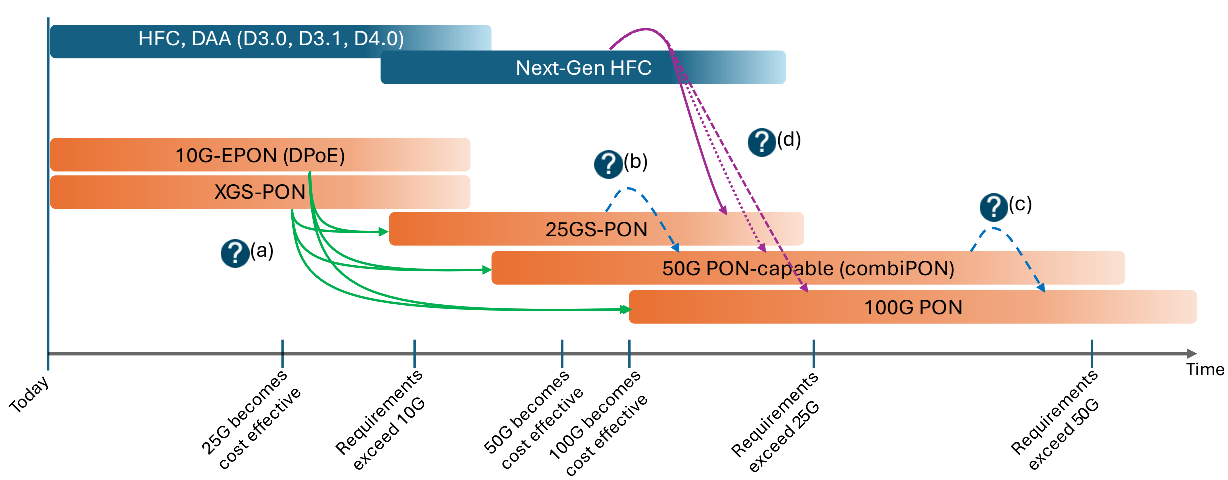

Figure 15 – Strategy with existing 10Gbps PON that parallels continuous HFC upgrades

Given that this operator has already deployed 10Gbps PON, they are likely not under pressure to choose a strategy in the short term. If the operator has deployed 10G-EPON, it is most likely with DPoE. In this case the operator should be anticipating a transition to 25Gbps, 50Gbps or 100Gbps PON and most likely to an ITU-T based PON. This transition could force a back-office integration effort and the operator would be wise to be developing a plan and architecture now rather than waiting. Operators that are currently deploying XGS-PON will likely have already solved the back-office integration and, shown as item (a) in Figure 15, will primarily need to focus on choosing between 25GS PON, 50G PON, and 100Gbps PON.

7. Conclusion

The rate of growth of demand in the access network remains difficult to estimate, but many models agree that the growth is slowing. Even so, the industry could realize a need for 50Gbps data rates in the access network by the year 2030. It is important for operators to plan for this eventuality and to be prepared for unexpected changes in the market that might cause consumer behavior to suddenly change like it did during the COVID-19 pandemic. This paper provides an overview of modern Passive Optical Network (PON) technologies, including 10Gbps, 25Gbps, 50Gbps, and 100G Coherent PON. Each technology presents unique technical merits, deployment scenarios, and economic considerations, which are crucial for broadband service providers planning their network upgrades and expansions.

Key points to consider include:

1. ***Technological Merits***: Understanding the strengths and limitations of each PON technology is essential. This includes factors such as maximum usable capacity, product availability, interoperability, and integration with back-office systems.
2. ***Deployment Scenarios***: Service providers must evaluate their specific needs and deployment scenarios. Factors such as existing network infrastructure, competitive pressures, and future scalability should guide the selection of the appropriate PON technology.
3. ***Economic Considerations***: Cost remains a significant factor in decision-making. This involves assessing initial capital expenditure, long-term operational costs, and the economic feasibility of upgrading to higher capacity technologies as demand grows.
4. ***Interoperability and Integration***: Ensuring seamless interoperability between different vendors' equipment and smooth integration with existing back-office systems is crucial for operational efficiency and customer satisfaction.
5. ***Future-Proofing***: The EPON vs. GPON debate seems to be coming to an end. However, there are now multiple ITU-T based PON technologies available today. It is vital to consider future-proofing strategies to ensure the best choice that minimizes cost while meeting demand for capacity and other features. This includes planning for potential upgrades to 50G and even 100G PON technologies to stay ahead of demand and maintain competitive advantage.

The choice of PON technology must be tailored to the specific requirements and strategic goals of each operator. By carefully considering the technological, economic, and operational factors discussed in this paper, providers can make informed decisions that optimize their network performance, enhance customer experiences, and ensure sustainable growth in the dynamic broadband market.

Abbreviations

ARPA	American Rescue Plan Act
BBF	Broadband Forum
BEAD	Broadband Equity, Access, and Deployment
bps/Gbps/Mbps	Bits per second / Gigabits per second /Megabits per second
CIN	Converged Interconnect Network
CM	Cable Modem
CMTS	Cable Modem Termination System
DOCSIS	Data Over Cable Service Interface Specification
DPoE	DOCSIS Provisioning of EPON
DSC	Digital Subcarrier
DSP	Digital Signal Processor
EPON	Ethernet Passive Optical Network
FEC	Forward Error Correction
F1 Fiber	Fiber cable from hub/central office to first cross connect
F2 Fiber	Fiber cable from first cross connect to second cross connect
F3 Fiber	Fiber cable from second cross connect to third cross connect
FTTP	Fiber to the Premises
HFC	Hybrid Fiber-Coax
Hz	Hertz
IM-DD	Intensity Modulation with Direct Detection
MDU	Multi-Dwelling Unit
MTA	Multimedia Terminal Adapter
NRZ	Non-Return to Zero
OLT	Optical Line Terminal
OMCI	Optical Network Unit Management and Control Interface
ONU	Optical Network Unit
OSP	Outside Plant
PAM4	4-level Pulse Amplitude Modulation
PON	Passive Optical Network
RDOF	Rural Digital Opportunity Fund
RGW	Residential Gateway
SC	Single Carrier
SCTE	Society of Cable Telecommunications Engineers
SDN	Software-Defined Networking
SOA	Semiconductor Optical Amplifier
STB	Set-Top Box
VNF	Virtualized Network Function
WFH/VPN	Work From Home/Virtual Private Network
XG-PON	10 Gigabit-capable Passive Optical Networks
XGS-PON	10 Gigabit Symmetrical Passive Optical Networks

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