Scaling of Current PON Technologies to Meet the CPON Goals of 100Gbps and Beyond

A Technical Paper prepared for SCTE by

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1. Introduction

Passive Optical Network (PON) is a fiber-optic telecommunications network that uses point-to-multipoint architecture to provide high-speed data, voice, and video services to subscribers. PON is the dominant solution to provide broadband services using fiber to the premises (FTTP). Operators look to expand access to more people and geographically remote areas in a cost-effective method. There is a need for new PON technology with higher capacities and longer reach and CableLabs has launched the Coherent PON (CPON) project to future-proof operator networks and deliver 100Gbps over PON (with coherent optical technology). Adapting existing standards to this new CPON technology is an advantageous approach. This needs an investigation of existing standards, to understand how to scale them to the speeds and capacities of CPON, which is the main goal of this paper.

EPON (Ethernet Passive Optical Network) and GPON (Gigabit Passive Optical Network) are two main PON technologies and cable operators are deploying both. While these PON technologies share similar architecture and topology they differ in many ways. This paper discusses the similarities and differences for the latest version of these technologies (ITU-T [GPON-G.HSP] and IEEE [Nx25G-EPON]). The focus will be on understanding the different layers of each technology and discussing the functional equivalence between the two and areas where they differ from each other.

Reusing technology layers from existing standards saves development time. Also, reusing many of the components of ASIC/silicon design implementations will reduce the cost of this new CPON solution. This paper highlights different factors of the existing GPON and EPON technologies that will need to be modified to reach these goals. This analysis includes a study of aspects such as the framing sublayer, fundamental line rates, effective data rates, FEC encoding/decoding, upstream scheduling/granting mechanisms, channel bonding, and provisioning etc. This paper aims to give an understanding of the current technologies and how those could be scaled to meet 100Gbps and beyond with CPON.

2. Overview of EPON

EPON is a point-to-multipoint technology that delivers 1/10/25/50Gbps upstream and downstream in FTTH/FTTP networks. 10G-EPON (defined in IEEE Std 802.3av-2009) supported backward compatibility with 1G-EPON (defined in IEEE Std 802.3ah-2004), allowing operators with existing 1G-EPON deployments to add 10G-EPON using either wavelength division multiplexing (WDM) for fully independent and parallel operation, or using time division multiplexing (TDM) for time-shared operation in the upstream direction.

The latest evolution in EPON technology is Nx25G EPON (defined in IEEE Std 802.3ca-2020) that enables 50Gbps in symmetric and asymmetric configurations, while maintaining backward compatibility with deployed 10Gbps EPON systems. Using a combination of 25Gbps (downstream or upstream) channels and/or 10Gbps (upstream only) channel, the resulting PON system can supports symmetric and/or asymmetric MAC data rates of:

- 25Gbps, downstream and 10/25Gbps, upstream (25G-EPON)
- 50Gbps, downstream and 10/25/50Gbps, upstream (50G-EPON)

Collectively, these systems are referred to as Nx25G-EPON, with parallel 25G-channels, operating on separate wavelength channels, and supporting channel bonding for an increased aggregate MAC data rate.

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2.1. EPON PHY Layer

In [Nx25G-EPON] technology, wavelength allocation allowing concurrent operation for downstream and upstream PHYs are shown in Table 1 below.

Table 1 – Downstream and Upstream Wavelength allocation EPON

Direction	Wavelength name	Center wavelength (nm)	Wavelength range (nm)
Downstream	DW0	1358	± 2
	DW1	1342	± 2
Upstream	UW0	1270	± 10
	UW1	1300	± 10
	UW2	1320	± 2

Most commonly, ODNs today are designed for compatibility with 10G-EPON PR30 power budget, supporting ODNs with 29dB optical loss. Nx25G-EPON accommodates channel insertion losses equivalent to 10G-EPON-defined PR20 and PR30 power budgets.

The physical coding sublayer (PCS) in Nx25G-EPON is responsible mainly for converting the data stream received from xMII into codewords, which can then be passed through PMA, PMD, and finally transmitted on the medium. In the receive direction, PCS performs the reverse function, i.e., decodes the received data and recreates the original data stream, hands off to the MCRS and then towards the Ethernet MAC and any associated MAC clients.

[Nx25G-EPON] uses 256b/257b line coding, the interleaver and de-interleaver are realized by using omega networks and it uses a stronger quasi-cyclic QC-LDPC FEC (with a much longer codeword but also providing a much higher degree of protection against bit errors).

2.2. EPON MAC Layer

Nx25G-EPON operates in a point-to-multipoint mode, delivering logically tagged Ethernet frames to subtended ONUs using a broadcast across the passive fiber ODN. In the upstream (from the ONUs towards the OLT), Nx25G-EPON operates in the multipoint-to-point mode. ONUs are allowed to transmit data only when they are explicitly granted by the OLT. The Nx25G-EPON architecture is based on multiple channels bonded together, 25Gbps in the downstream and 10Gbps/25Gbps in the upstream. Figure-2 shows the PHY and MAC layer components on the EPON network devices.

The multi-channel reconciliation sublayer (MCRS) provides logical channel bonding between any MAC and any number of underlying physical layers (channels), data is striped across multiple physical channels in both directions. MCRS is an interface between the MAC sublayer and one or more xMIIs. xMII is a generic term for the Media Independent Interfaces, for 25 Gb/s implementations, it is called 25GMII MCRS adapts the bit-serial data stream received from the MAC layer to the parallel format of the PCS service interface, effectively stripping Ethernet frames across multiple physical channels. Each and every PCS instance represents an MCRS channel, carrying data units between OLT and ONU.

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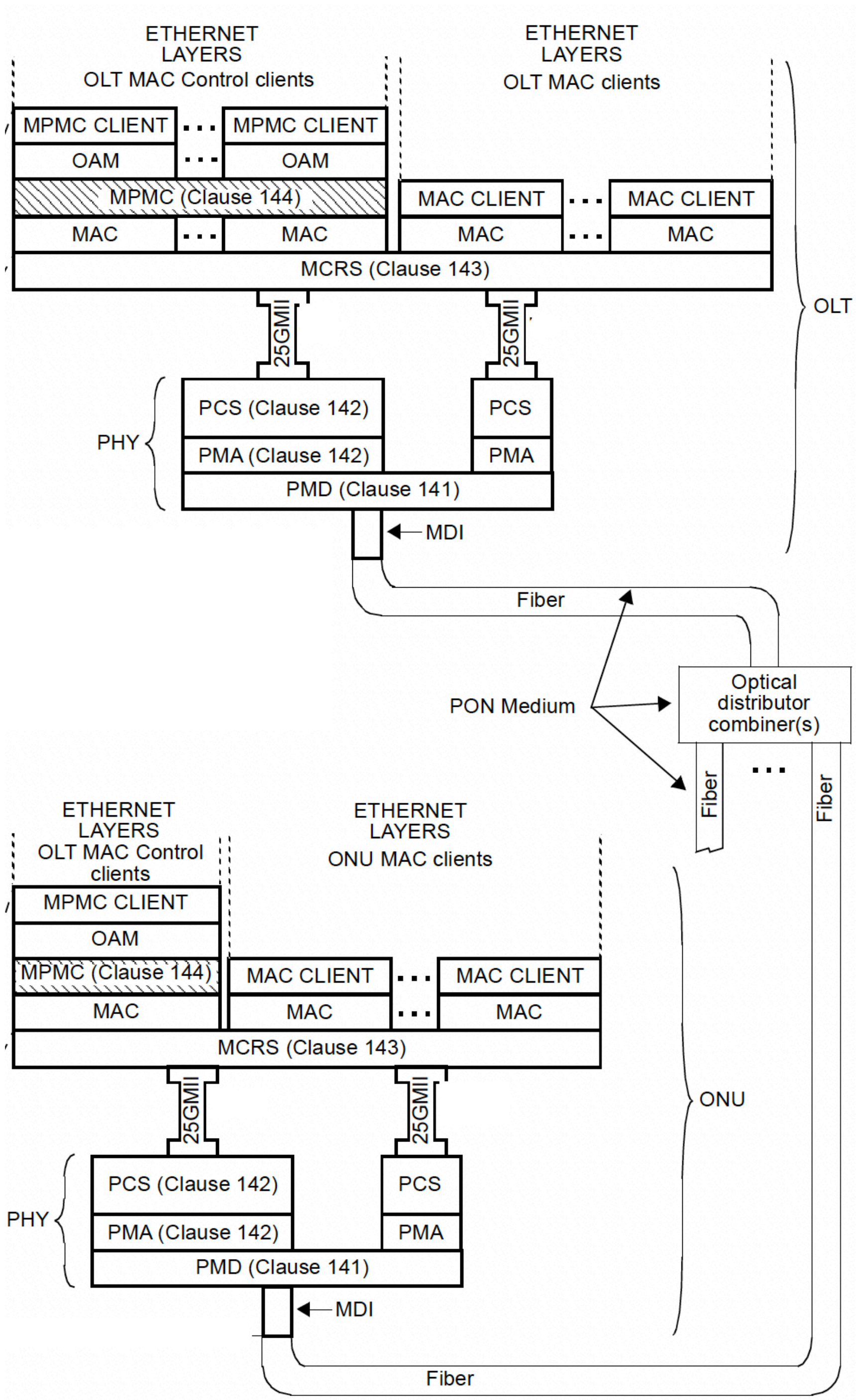

Figure 1 – Nx25G EPON PHY and MAC Layers

Source:*IEEE-Std-802.3ca-2020:*Figure 144–2

All multi-channel variants of the system rely on channel bonding, allowing for a single higher speed MAC (e.g., 50Gbps transmitting over a pair of bonded 25Gbps channels in a manner that is completely transparent to MAC). The resulting system architecture is scalable, allowing future revisions of the system to add individual channels, as well as replace channel definitions, data rates, FEC encoding, etc.

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2.3. Provisioning (OAM, DPoE OAM, IEEE 1904.1, 1904.4)

IEEE Standard for Service Interoperability in EPON (SIEPON) defined in IEEE Std 1904.1 & IEEE1904.4, describes the system-level requirements needed to provide service-level, multi-vendor interoperability of EPON equipment. It complements the existing EPON standards, which enable the interoperability at the Physical Layer and Data Link Layer.

SIEPON enables system-level interoperability, covering equipment functionality, traffic engineering, service-level quality of service/class of service (QoS/CoS) mechanisms, service and equipment management etc. SIEPON provides requirements for the operation of ONU and OLT devices. To foster interoperability across the PON among equipment from different vendors, it specifies the flow of information exchanged between the ONU and OLT as well as their associated behaviors.

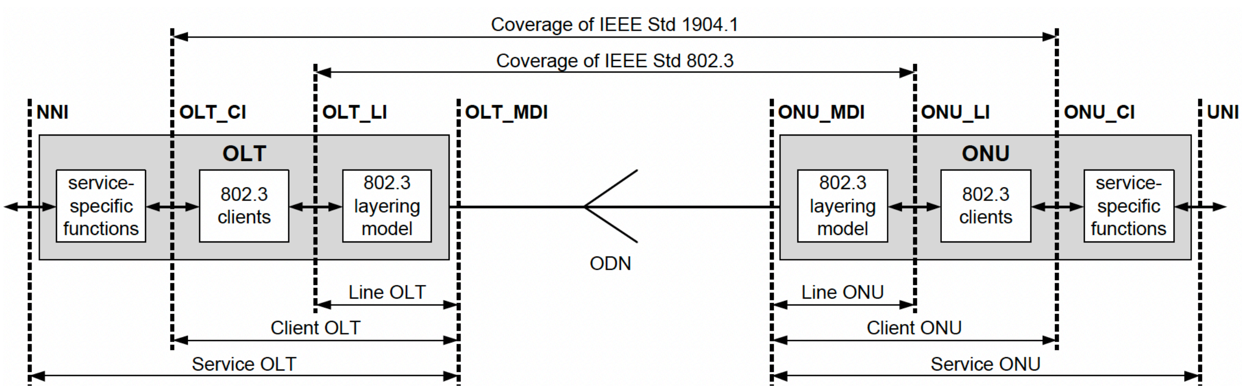

Figure 2 – Nx25G EPON SIEPON vs OAM

Source:*IEEE-Std-1904.1-2017:Figure 5-1*

IEEE Operations, Administration, and Maintenance (OAM) sublayer [IEEE 802.3], provides mechanisms useful for monitoring link operation such as remote fault indication and remote loopback control. OAM provides network operators with the ability to monitor the health of the network and quickly determine the location of failing links or fault conditions. The OAM provides data link layer mechanisms that complement applications that reside in higher layers.

3. Overview of ITU-T PON

The history of PON within the ITU-T dates back as far as 1987 when passive optical networking was proposed by British Telecom. The first PON specification, ITU-T G.982, (ATM PON or APON), was released in 1996. APON operated at 1.5Mbps and was followed in 1998 by BPON (Broadband PON) which operated at 622Mbps in the downstream direction. Several operators like Verizon deployed BPON prior to the release of the GPON, G.984 in 2003. GPON, operating at 2.5Gbps downstream and 1.25Gbps upstream, enjoys massive deployments around the globe to this day.

However, XGS-PON, (2016) has come to the forefront in the past several years and is positioned to be the most widely used PON technology ever. XGS-PON, specified in ITU-T G.9807, operates at 9.95328Gbps (typically referenced as a 10Gbps PON) in the upstream and downstream direction.

NG-PON2 was released as ITU-T G.989 in 2015. NG-PON2 was intended to add certain resiliency features and to boost aggregate network capacity up to 40Gbps of total capacity. While one large operator is committed to deploying NG-PON2, it will never see widescale deployment.

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3.1. ITU-T PMD Layers

The PMD layer of GPON, XGS-PON, and NG-PON2 are all based on intensity modulated laser transmission over single mode fiber with direct detection at the receiver (IM-DD). These support a range of optical power budgets to enable split ratios up to 1:128 and transmission distances up to 20km (40km with PON extender devices).

GPON uses a wavelength of 1490±10 nm for downstream transmission. G.984.2 specified 1310±50 nm for upstream transmission, but this has been narrowed in recent years to 1310±20 nm which opens some spectrum for new PON standards. XGS-PON uses a wavelength of 1575-1580nm for downstream transmission and 1280-1290nm for upstream transmission.

NG-PON2 achieves 40Gbps of aggregate capacity by allocating 4 lanes, each operating at 10Gbps. These lanes are allocated in upstream plus downstream pairs, sometimes referred to as channel pairs, Table 2.

Table 2 – Downstream and Upstream Wavelength allocation NG-PON2

Channel	Downstream Wavelength	Upstream Wavelength
1	1596.34nm	1532.68nm
2	1597.19nm	1533.47nm
3	1598.04nm	1534.25nm
4	1598.89nm	1535.04nm

50G-PON, specified in ITU-T G.9804, continues the use of IM-DD but increases the downstream nominal line rate to 49.7664Gbps. The currently released specification supports only 24.8832Gbps and 12.4416Gbps in the upstream but the specification for 49.7664Gbps in the upstream is expected to be released soon.

The optical spectrum for PON is very crowded in the O-band, but 50G PON is wedged in with a couple of options as shown in Table 3.

Table 3 – ITU-T-G.9804 50G-PON Wavelengths

Channel	Wavelength	Line Rate	Coexistence Impact
Downstream	1340-1344nm	49.7664Gbps	
UW2	1260-1280nm	12.4416Gbps	Displaces XGS-PON
UW1	1290-1310nm		Displaces GPON
UW2	1260-1280nm	24.8832Gbps	Displaces XGS-PON
UW1	1290-1310nm		Displaces GPON
UW1 Narrowband	1298-1302nm		Coexist with XGS-PON and GPON
Upstream	Work in Progress	49.7664Gbps	

3.2. TC-Layer

Each ITU-T PON specification includes a Transmission-Convergence Layer (TC Layer). The function and design of each is fundamentally the same but incorporates changes specific to the technology and needs at the time of the specification's release. The TC layer adapts the upper layer client entities to the underlying PMD and also includes the functions necessary to operate and manage the PON. [GPON-

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G.HSP], defines a Common TC Layer (ComTC) that is the most advanced, intended to be applied to 50G PON. ComTC defines three sublayers as shown in Figure 3. The Service Adaptation (SA) sublayer is responsible for encapsulating user data into XGEM frames and multiplexing XGEM frames into the framing sublayer.

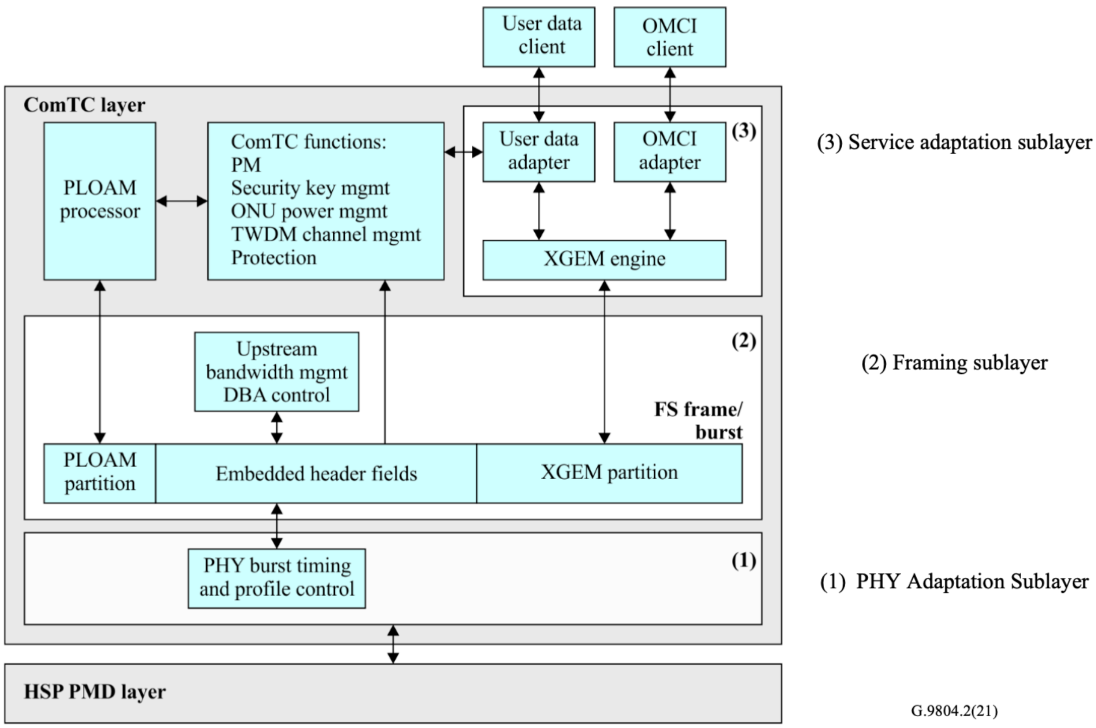

Figure 3 – GPON ComTC, PHY and MAC layers

Source:*ITU-G.9804.2-Figure6-3*

In the Framing Sublayer (FS), the XGEM data is encapsulated with overheads that are necessary to manage operation of the PON, primarily the Physical Layer OAM channel, which carries the information to manage the FS and PMD layer, and Embedded OAM data, which carries bandwidth allocation and dynamic bandwidth assignment fields. The PHY Adaptation sublayer enriches the bit stream to enable synchronization and time alignment of the bit stream and provides coding, scrambling and Forward Error Correction.

3.3. ONU Management

The Optical Network Unit (ONU) is the network terminal equipment located at the customer-side of the PON. The ONU is physically separate from the OLT and must be configured and managed, this is is supported by the ONU Management and Control Interface (OMCI) defined in ITU-T G.988.

OMCI has three main components: One is the Management Information Base (MIB) which specifies the database that enables configuration management, fault management, performance management and security management of the ONU. The MIB is described in terms of Managed Entities (ME) and their relationship to one another. The second component of the OMCI is the protocol used to convey the MEs between the ONU and the OMCI management function which is traditionally located in the OLT. The third component is the OMCI Management and Control Channel (OMCC) over which OMCI is

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conveyed. Since OMCI is simply a client to the ComTC layer, the OMCC is a special case of an XGEM port on the PON.

3.4. 25GS-PON MSA

The 25GS-PON MSA (October-2020) developed outside the ITU-T as a "delta spec". It is written to adopt the relevant GPON specifications and to adapt the EPON PHY to them by calling out specific differences that are detailed in the new specification. The 25GS-PON MSA is a delta specification that provides the "glue" between: [Nx25G-EPON] for PMD layer and FEC (LDPC), ITU-T G.9807.1 (requirements) for TC layer (G.987.3) a.k.a. XG(S)-PON 10G and ITU-T G.988 for OMCI and the BBF TR-385 for Yang models. Key differences in the 25GS-PON PMD layer are the wavelengths and the line rate as shown in Table below.

Table 4 – 25GS-PON wavelengths

Channel	Wavelength	Line Rate Gbps	Coexistence Impact
Downstream (DW0)	1358nm +/- 2nm	24.8832	
Upstream UW1	1300nm +/- 10nm	24.8832 or 9.95328	XGS-PON
Upstream UW2	1270nm +/- 10nm	24.8832 or 9.95328	GPON
Upstream UW3	1286nm +/- 2nm	24.8832 or 9.95328	GPON+XGS-PON

25GS-PON holds closely to the TC Layer for XGS-PON found in ITU-T G.9807.1. The most significant change in the TC layer is the adoption of LDPC FEC from [Nx25G-EPON]. The majority of the remaining changes are necessary only to adjust frame byte counts, preserve alignment while preserving the 125µs frame size.

4. Brief Introduction to CPON

The advent of coherent optics technology in fiber transport has brought about a paradigm shift in optical transmission systems, facilitating a comprehensive overhaul in the widespread DWDM networks operating at data rates such as 100Gbps, 200Gbps, and 400Gbps per wavelength. Over the past decade, the scope of coherent optics has transcended long-distance transports, extending its purview to metropolitan networks, and now into optical edge networks. The next domain that coherent is poised to enter is the realm of FTTP, primarily characterized by point-to-multipoint PON, a revolutionary step for 100G PON and beyond. The utilization of coherent optics within a PON, known as Coherent PON (CPON), yields numerous advantages by implementing multi-dimensional modulation and coherent detection and digital signal processing techniques to achieve unprecedently high degree of flexibility in terms of transmission distance, split ratio, and the optical access architecture.

4.1. PHY Technology

Compared to alternative direct-detect solutions that just use amplitude (one dimension only) to represent the signal, coherent optical solutions use a local laser source as a reference to achieve linear conversion of the optical field instead of optical power used in direct detection. This enables modulation and detection using four independent degrees of freedom, including amplitude and phase in two polarizations. With a local oscillator, significant coherent gain is provided along with wavelength selection without the need of an optical filter. Additionally, power fading induced by chromatic dispersion in direct-detection systems is no longer an issue because of optical field recovery in coherent detection. These features coherent optics bring to optical transport systems, enable greater modulation efficiency and receiver sensitivity.

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Coherent detection for short-haul networks enables a superior receiver sensitivity that allows for extended power budget. The multi-dimensional signal recovered by coherent detection also compensates for linear transmission impairments such as chromatic dispersion and polarization mode dispersion. The efficient use of fiber spectral resources results in more optical spectrum available for future use and enables future network upgrades through the use of multi-level advanced modulation formats.

CPON exhibits substantial potential for optimization and advancement across the optical, electrical, and digital domains. This includes extended reach, eliminating the necessity for repeaters, reducing real estate costs associated with cabinets and flexibility to accommodate diverse deployment scenarios through adaptable topology. It introduces operational simplicity by minimizing the number of ports and links that require management and prolonged technological lifespan, negating the frequent need for upgrades.

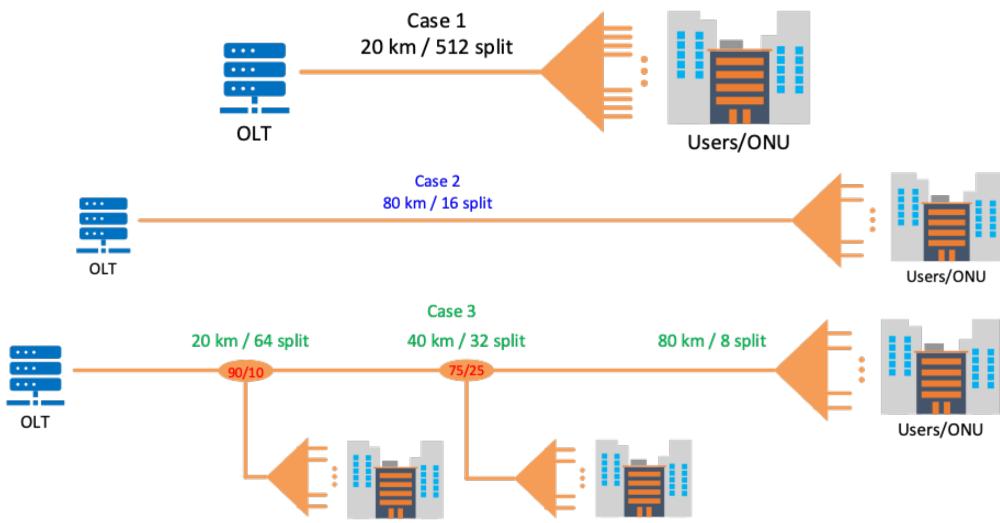

Figure 4 –CPON application scenario illustrations

Figure 4.1 illustrates 100G CPON target topology options. Case 1 involves opting for an elevated split ratio over a limited distance. For instance, a 512 split configuration is achievable at a transmission distance of 20 km, well-suited for situations requiring a high-density network in close proximity. Conversely, Case 2 demonstrates an alternative strategy emphasizing a reduced split ratio over an extended transmission distance. A 16 split configuration is demonstrated at 80 km of transmission distance, catering to rural applications where longer reach is imperative. Case 3 introduces a hybrid mode wherein various split ratios are judiciously combined across different transmission distances. Specifically, this involves a CPON port initially tapped at 20 km using a 90/10 passive splitter, thereby accommodating 64 splits. This is followed by a 40 km tap employing a 75/25 passive splitter, facilitating 32 splits. Finally, at a distance of 80 km, an additional 8 splits are supported. Case 3 is indicative of a distributed CPON architecture, strategically designed to optimize the conveyance of optical power over passive ODNs. In this dynamic context, each coupler diverts a predetermined portion of the CPON signal to a localized splitter equipped with a suitable number of ports, meeting demands of local ONUs. The integration of adjustable and remotely controlled couplers introduces a layer of automation, streamlining operational procedures.

4.2. Target Applications

CPON supports fiber-to-the-home (FTTH) connectivity, direct fiber connection to either multiple dwelling units or single-family units. In brownfield FTTH deployments with existing IM-DD PON, a

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CPON network could be overlayed using Coexistence modules, allowing the operator to gracefully migrate certain customers to increase revenue opportunities or lower congestion for other customers on the ODN. CPON can support back-haul connectivity to the aggregation node. The aggregation node can contain Remote PHY devices (RPDs) and Remote MAC-PHY devices (RMDs), to support distributed Converged Cable Access Platform (CCAP) architectures. CPON can be utilized to provide base station connectivity, carry back-haul traffic in 5G RAN and also carry traffic from the mid-haul/front-haul segment of 5G RAN. Beyond these, CPON can find applications in Wi-Fi access, edge computing, IoT-based Smart City connections, etc. enhancing connectivity across diverse scenarios. The 100Gbps target is only a starting point, and the plan is to scale further in the future.

5. Comparison and commonalities

Both the GPON and EPON systems enable flexibility to support higher performance physical media dependent (PMD) interfaces without impacting the definition of the associated MAC and higher level PHY layers. This section looks at some of the commonalities, past approaches at unification and a potential path forward for a new technological development like CPON.

5.1. Comparison and commonalities of EPON and GPON

GPON and EPON provide a system that can be adapted to different line rates, number of wavelength channels, and signal modulation etc. Both GPON and EPON systems are layered in a similar fashion, supporting physical layer technology which physical transmission of data over the optical medium and a data link layer technology to enable point to multi point communication between OLTs and ONUs.

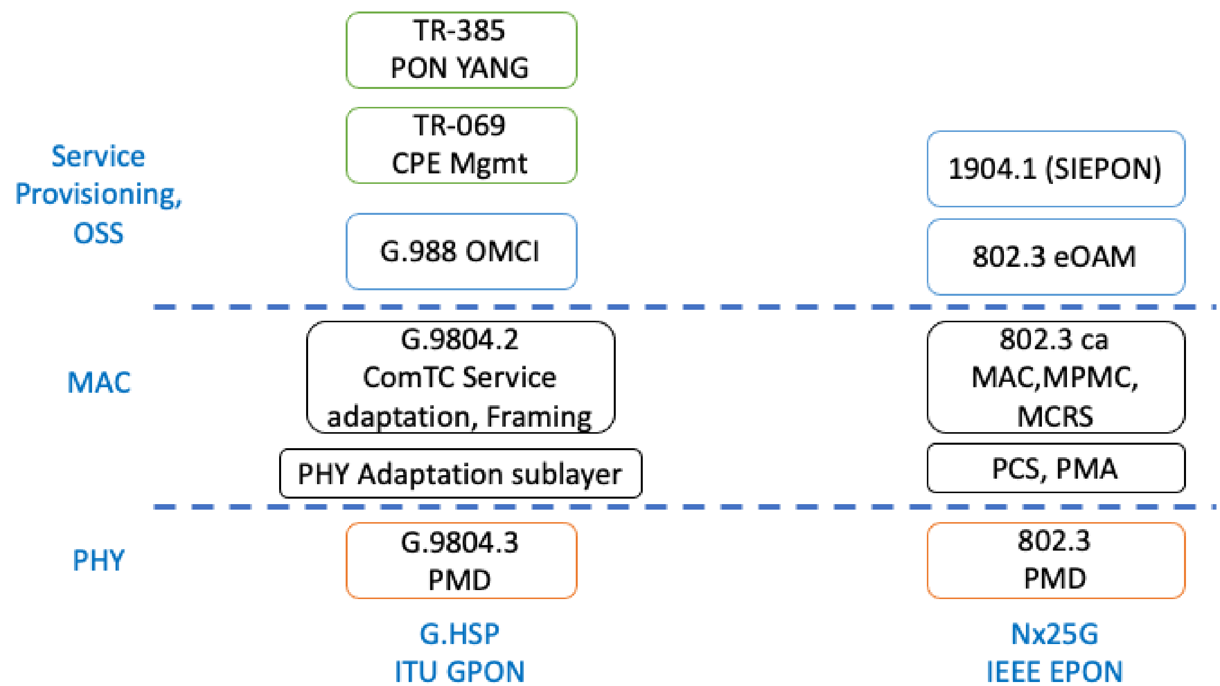

Figure 5 –PHY, MAC& OSS technology stacks for GPON& EPON

Figure 5 summarizes the various technology layers in GPON and EPON and tries to align the functionality, the horizontal lines to indicate equivalence. At the physical layer, both technologies define a PMD (physical media dependent) layer. Above the PMD, is the layer which connects the MAC to the PHY, PHY Adaptation sublayer (in GPON) and PCS, PMA layers (in EPON), these define the FEC parameters, burst profiles, interleaving etc. The MAC layer above that defines how the data is framed and sent across one or multiple PHY channels. EPON allows for combining multiple PHY channels together (MCRS) , and at this time GPON does not have a solution for aggregating multiple channels.

5.2. One PON

There are two main camps in the development of PON standards: ITU-T PON and IEEE EPON, Figure 6. These camps share common requirements, particularly in terms of ODN and PMD aspects, the higher-cost components in deployment. The similarity in network architecture contributes to similar ODN designs, which demands similar PMD technical requirements. This allows for leveraging the same shared pool of optical components.

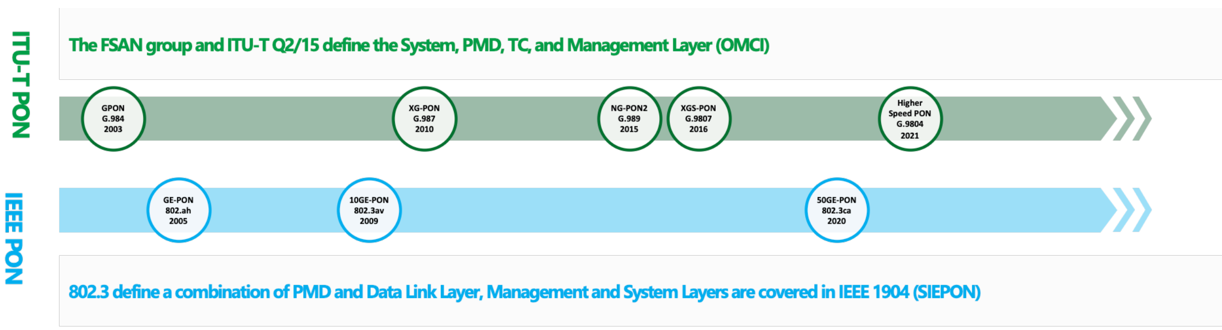

Figure 6 – Two Different PON Camps

However, the two camps differ significantly in their approaches for various aspects of the layered structure of the upper layer and network management. This encompasses distinct framing, timing, adaptation, and PLOAM message handling methods. The desire to unite these two camps has been present for a long time, because having a single PON standard, referred to as One PON, offers operators the advantage of achieving broader PON deployment while maintaining a clear evolutionary path. This, in turn, would lead to increased volume and subsequently drive down costs. However, this endeavor has not proven successful thus far.

Based on market deployment statistics from both OLTs and ONUs, there is approximately an 8:1 ratio in favor of ITU-T PON compared to IEEE EPON. Given ongoing trends, it seems challenging for this unification to succeed in the immediate future as well. The reasons include the diverse composition of members within the two camps, differing design philosophies, and the distinct FTTx/PON roadmaps pursued by various operators in both established and new deployment areas. Due to the complexities and challenges involved in designing and developing the next-gen PON, particularly the need for a common Physical Layer (optoelectronic components and ASICs) to share costs, industry experts are still working towards convergence. The revolutionary 100G or 200G CPON might hold the potential to realize this convergence, given its capability to innovate and address these challenges.

5.3. MAC Layer Approach for CPON

Both EPON and GPON have their own advantages and are used in various deployments around the world. The choice between the two depends on factors such as the required data rates, compatibility with existing infrastructure, and specific service offerings. Additionally, there has been an evolution in both families of PON technologies to provide higher data rates and capabilities. At this point, we are recommending a dual

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path approach, to build a solution which will fit in with both the GPON and EPON MAC and higher layer technology stacks.

5.3.1. Why two MACs for CPON?

EPON and GPON remain among the most widely adopted PON technologies. The opportunities for PON equipment vendors are continuing in developed and developing countries. Some operators are selectively adding FTTH while other operators see an opportunity for PON infrastructure to support both residential and non-residential subscribers and applications. The adoption of 10G PON (XGS PON and 10G EPON) in developed markets motivated vendors, providing the opportunity to support higher speeds at lower cost compared to 1G EPON and 2.5G GPON.

While the current GPON and EPON market opportunity is sufficiently large, we reason that the market is unlikely to accept a third PON standard, and economically support a third type of PON technology. Hence our thought process is to align the new CPON technology with the current EPON and GPON technology, by adding the new CPON PHY layer technology to fit and work with both the existing EPON and GPON higher layer MAC technologies.

Reusing as much as possible from existing standards lowers the time to produce the technology versus completely creating a new PON MAC and higher layer from scratch to go with the new CPON PHY. Reusing portions of the existing silicon design components also reduces relative cost for a CPON solution.

5.3.2. Delta Specifications

The CPON working group is taking on a delta approach to 'glue' the CPON PMD under the two existing PON standards: IEEE [Nx25G-EPON] and ITU [GPON G.HSP]. Reusing technology and staying focused on getting the new CPON PHY to work with existing MAC layers minimizes the time to market.

EPON and GPON technologies have been heavily vetted by multiple PON vendor companies. As a precedent, the 25GS-PON MSA effort reused much of those technologies, and this approach was proven by product demonstrations in the market in about two years after the 25GS-PON MSA was formed.

For CPON, a separate delta specification will be required for each standard, i.e., a single CPON PMD specification will be interfaced with both [Nx25G-EPON] and [GPON-G.HSP]. The idea is to create a CPON PMD specification that is a "drop in" for an [Nx25G-EPON] PMD and [GPON-G.HSP] PMD, Figure 7. The proposal is to re-use the [Nx25G-EPON] LDPC mother code, with codeword length and puncturing adjustments as needed. The goal is to specify "delta" details for any higher layer adjustments, such as: Data rate, Framing, Synchronization, Channel skew, Grants: Gates, BWmap, etc. For channelization [Nx25G-EPON] defines two channels, each consisting of a downstream and upstream wavelength, originally intended to support up to four channels (pairs). G.9804.3 PMD Table 9-5 on specifies one downstream wavelength and two upstream wavelengths TWDM extends to 8 channel pairs.

As regard management and OSS protocols for both of these systems, work will likely be needed to develop management layer plane configuration for the new CPON physical layer/ PMD. Further detailed study is needed for ITU-T PON (with PLOAM and OMCI) and IEEE EPON (with OAM and SIEPON).

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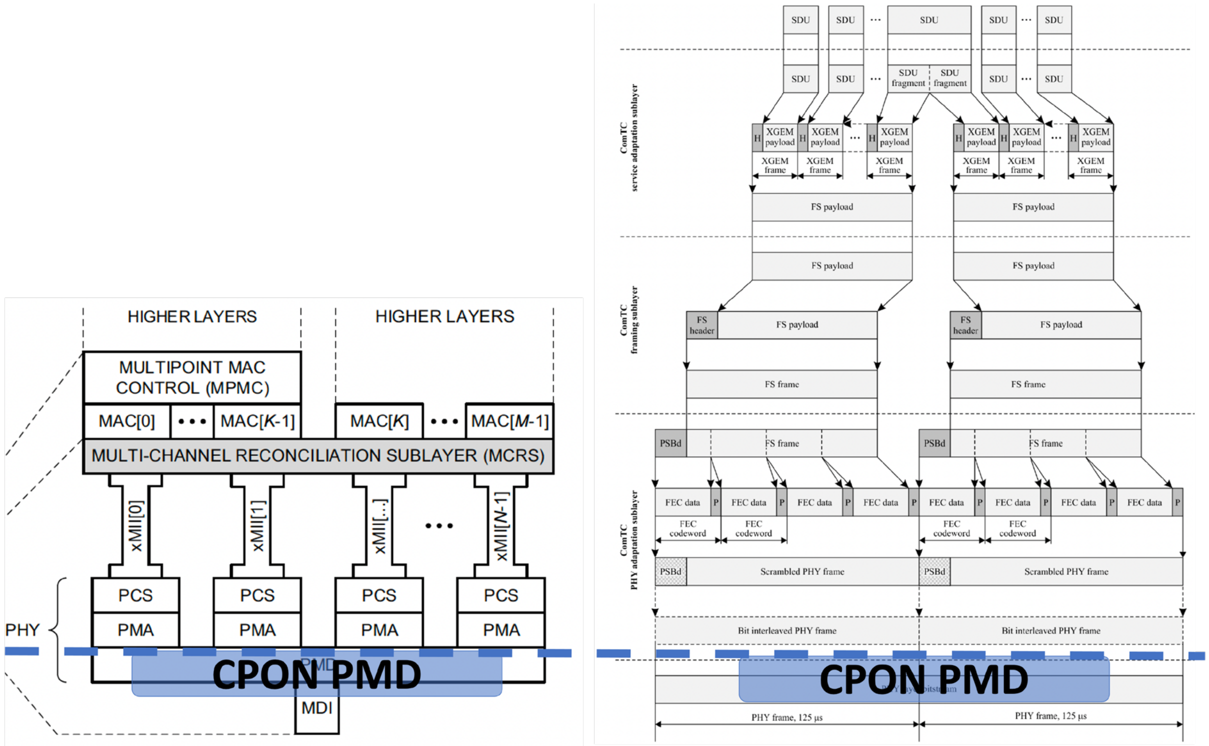

IEEE Nx25G EPON

ITU G.hsp GPON

Figure 7 – A Drop-in CPON PMD for both EPON & GPON tecnology stacks

Source:*IEEE-Std-802.3-2022,*and *ITU-G.9804.2*

6. Scaling Considerations for CPON

Scaling from existing (EPON and GPON) MAC layer technologies to the latest CPON is possible with careful consideration. In this section we think through how the current technologies work and how scale them to the speeds and capacities of CPON. With a goal of at least scaling to 100G and beyond in future generations it needs tweaking of the current EPON and GPON implementations for the future.

6.1. EPON based MAC Layer

This section starts to dig deeper into the [Nx25G EPON] technology PHY-MAC interfaces and look at the framing and data rates. We investigate the MCRS, 25GMII, and the PCS layers to understand the current capacity and overheads. We then discuss methodologies on how to scale the existing Nx25G EPON technology to scale to 100Gbps and beyond to meet the goals of CPON.

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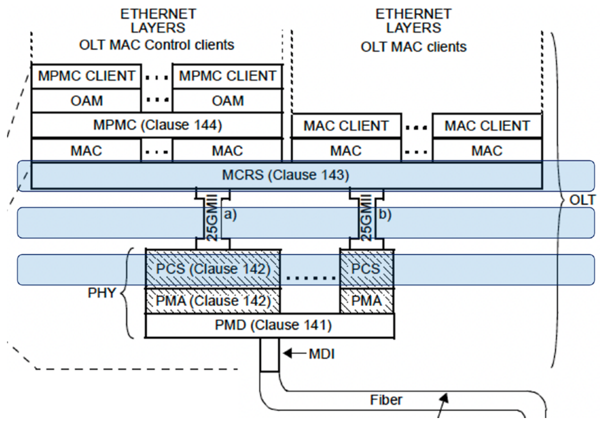

Figure 8 – Analysis of the line,frame , data rates on EPON tecnology stack

Source:*IEEE-Std-802.3ca-2020:Figure 144–2.*

6.1.1. Understanding EPON Overheads

6.1.1.1. Multi-Channel Reconciliation Sublayer

The MCRS adapts the bit-serial data stream received from an Ethernet MAC to the parallel format of the PCS service interface, across multiple physical channels. Each PCS instance represents an MCRS channel, that operates on envelope quantum (EQ) data units (consisting of eight control bits followed by 64 bits of data). Effectively, a single EQ comprises data from two consecutive medium independent interface (MII) transfers, with re-arranged data and control symbols, Figure 9.

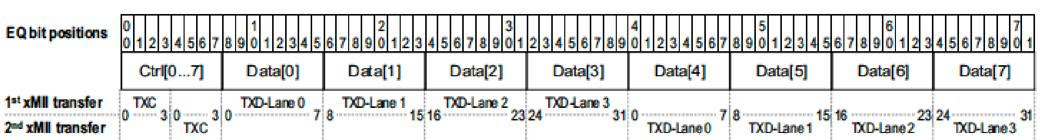

Figure 9 – Envelope Quantum Format in EPON

Source:*IEEE-Std-802.3ca-2020:Figure 143–2.*

The user data is split up into multiple of these EQ data units, with an envelope start header (ESH) and multiple envelope continuation headers (ECH). Only the ESH needs to be counted in overhead calculations, ECH doesn't count as it is used in place of a data preamble.

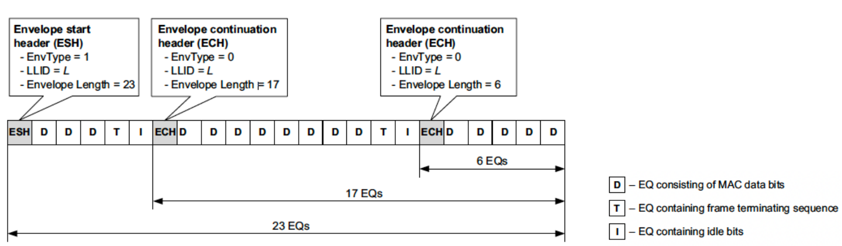

Figure 10 – Transmission Sequence consisting of three frames

Source:*IEEE-Std-802.3ca-2020:Figure 143–3.*

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Table 5 – MCRS Envelope Quantum Capacity

Layer	Size(bits)
User data	14272
EQ Data	64
EQ Control	8
EQ total bits	72
Number of Data EQs (= user data/ EQ Data)	223 (EQs)
EH (ESH or ECH = 1 EQ)	64
Number of EH	1 (EQ)
Control	8
EH + Number of data EQs	14336

For user data we are starting with 14272 bits, just as an example as this happens to fit within a codeword after some of the overheads.) and is transformed into 14,336 bits of data coming out of the MCRS.

6.1.1.2. Specific Media Independent Interface (xMII)

The Media Independent Interface (xMII) provides an interconnection between the MAC layered and the PHY layers. The Nx25G EPON 25GMII is capable of supporting 25Gbps data rates. The structure of each of the 25GMII interfaces in an MCRS system has a clock rate of 390.625 MHz, Table 6.

Table 6 – 25GMII Clock rate

Layer	Rate
MAC Data Rate	25Gbps
Time to move 1 EQ of data. 64 bits @ 25Gbps (2x32 + 2x4 ctrl)	2.56ns
25GMII Clock rate	390.625MHz

6.1.1.1. Physical Coding Sublayer PCS

The Physical Coding Sublayer (PCS) defines the 256/257B transcoder, scrambler, the FEC encodings and burst transmission sync patterns etc. used within EPON.

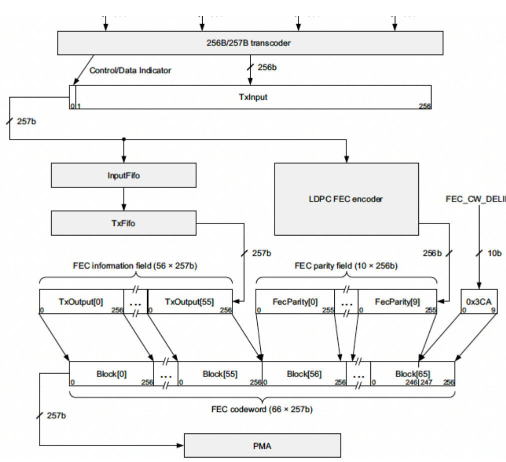

Figure 11 – EPON Physical coding sublayer

Source: *IEEE-Std-802.3-2022:Figure 142–4*

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Table 7 walks through the transformation the user data goes through at the PCs layer. The PCs layer operates on 256 bits at a time and ultimately outputs LDPC FEC code words off the size 16,962 bits.

Table 7 – PCS Layer Data rate calculations

Layer	Size(bits)
PCS User Data	256
Data after 256b/257B encoding	257
Number of FEC data blocks in a codeword	56 blocks
FEC data per codeword (256 * 56)	14336
FEC payload (257 * 56)	14392
FEC Party block size	257
Number of Parity blocks in a code word	10 blocks
FEC Parity	2570
FEC CW Size (FEC Payload + FEC Parity)	16962

Now for the upstream direction in the PCS layer, there is an additional upstream burst overhead. The ONU upstream burst begins with a synchronization pattern and ends with a termination sequence, which are not FEC protected. The synchronization pattern comprises of SP1 zone, optimized for laser on (Ton) and automatic gain control (AGC, Trx_settling); SP2 zone, optimized for clock and data recovery (T_{CDR}); and SP3 zone, optimized for the start-of-burst delimiter (SBD) pattern. Each SP zone is a multiple of 257 bits, aligning with the PCS line code of 256B/257B. The upstream burst ends with an end-of-burst delimiter (EBD). When received at the OLT, the EBD pattern allows for the rapid reset of the OLT FEC synchronizer, preparing the OLT for the next incoming upstream burst.

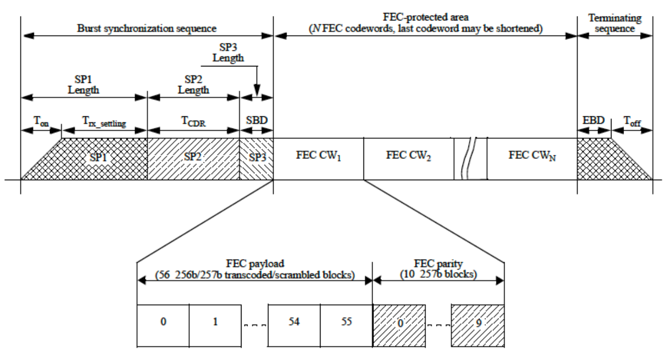

Figure 142–3—ONU burst structure, 3 zones

Figure 12 – ONU Burst Structure

Source:*IEEE-Std-802.3ca-2020:Figure 142-3*

The range of the upstream PHY overhead in time for 25G EPON is around ~500ns. (528.330ns as calculated in the table below). For CPON the expected range is in the range of 300 ~ 500ns.

Table 8 – Upstream PHY Layer Burst Overhead

Upstream	bits	Time(ns)
SYNC Pattern size	257	9.968
SP1 (20*SP)	5140	199.370
SP2 (20*SP)	5140	199.370
SP3 (1*SP)	257	9.968

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Upstream	bits	Time(ns)
Burst Sync Sequence (SP1+SP2+SP3)	10537	408.708
EBD	257	9.968
Laser off time, Toff	771	29.905
Terminating Sequence (EBD+Toff)	1028	39.874
Guard time (between bursts)	2056	79.748
US PHY Overhead per burst (BurstSyncSeq+TermSeq+Guard)	13621	528.330

6.1.1.2. Data rate Calculations

Given overheads in the downstream and upstream and the clock rates, one can calculate the effective data rate obtained in EPON. The 'Line Rate' is defined as the number bits/second transmitted on the fiber. The 'Data Rate' is the effective user data throughput.

For downstream data rate, Table 9, shows the line rate after the xGMII, and uses that rate to find the time it takes to transmit one full code word. Based on that time it calculates the data rate or the effective data throughput obtained in the downstream.

Table 9 – Downstream Data rate calculations

Layer	Rate
Line rate after 25GMII (25Gbps * 64/66)	25.78125Gbps
Time to transmit 1 CW. (FEC CW Size / Line rate)	657.92ns
Data rate for data bits (FEC Data per codeword / Time to transmit 1 CW)	21.790Gbps

For upstream data rate, Table 10, calculates the data throughput in a similar fashion.

Table 10 – Upstream Data rate calculations

Upstream	Rate/Size
Upstream line rate	25.78125Gbps
FEC CW Size	16962bits
US PHY Overhead per burst	13621bits
US FEC CWs (assume number of codewords in burst)	100cw
US FEC CWs + PHY burst Overhead	1709821bits
FEC Data bits only	1433600 bits
Transmit Time for US FEC CWs (FEC+PHYoverhead / upstream line rate)	66320.3297ns
US Data rate (data bits only) (FEC data / Transmit time for USFEC CWs)	21.616Gbps

6.1.2. Scaling of EPON technology for CPON data rates

As proposed if we build a CPON PMD to the EPON MAC, then we have a few options in terms of changing existing rates within EPON to allow us to scale to the CPON 100Gbps+ target service rates. Here are some of the options to change scale, for CPON starting with [Nx25G-EPON] based upper layers.

- If CPON decides to go down the route of multiple subcarriers then it can use 4 subcarriers, each at 25Gbps, and perhaps 8 subcarriers in the future.
- If CPON decides on a single channel PON i.e., just one carrier, then the MAC would need to change to handle higher speeds, this can be done in a couple of ways.
    - CPON could increase from the current 25 Gbps MAC data rate to a 100 Gbps data rate. This would mean that we would need to increase the xGMII Clock rate by four times,

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390.625x4 → 1562.5MHz. It needs to be investigated if it is possible to cost effectively build designs at this high clock rate.
- Another option is to design a new xGMII, with a larger bit width: i.e., from supporting 64-bit transfers now to supporting 256-bit transfers. This is a bigger effort given that the XGMII interface is vetted by the EPON community and needs to go through that process.

It also makes sense to align with the 100 Gigabit Ethernet Applications and make sure that the line rates can support this. Table 11 shows the line rates and data rates achievable by simply multiplying the number of 25Gbps channels, it shows some of the choices in getting to the 100Gbps mark. As we can see in the table below, a multiplier of 4 gets us to a line rate above 100Gbps second and multiplier of five gets us to a data rate above a 100Gbps.

Table 11 – Potential Multipliers for Data rates

	Line Rates Gbps		Data Rates Gbps	
Multiplier	**DS**	**US**	**DS**	**US**
1	25.781	25.781	21.790	21.616
2	51.563	51.563	43.580	43.233
3	77.344	77.344	65.370	64.849
4	103.125	103.125	87.160	86.465
5	128.906	128.906	108.949	108.081
6	154.688	154.688	130.739	129.698
7	180.469	180.469	152.529	151.314
8	206.250	206.250	174.319	172.930
9	232.031	232.031	196.109	194.547
10	257.813	257.813	217.899	216.163

6.2. GPON based MAC Layer

This section starts to dig deeper into the ITU [GPON-G.HSP] technology PHY-MAC interfaces, framing and data rates. In attempting to evaluate the potential performance of a 100Gbps PON that adopts the ITU-T model of PON, it is necessary to understand the Common Transmission Convergence (ComTC) layer and its sublayers: Service Adaptation, Framing, and PHY adaptation sublayers. We investigate these below to compute the current capacity and overheads and discuss methodologies on how to scale these to 100 Gbps and beyond.

6.2.1. Understanding GPON Overheads

6.2.1.1. XGEM Framing

The Service Adaptation layer receives user data, Service Data Units (SDU), from client applications. Once received, the SA sublayer encapsulates the SDU in an XGEM frame, Figure 13. SDUs are allowed to be fragmented, but most modern networks are based on Ethernet frames, and ComTC does not permit Ethernet frames to be fragmented. There is nothing in the XGEM frame that would need to change to enable ComTC to scale up to 100Gbps.

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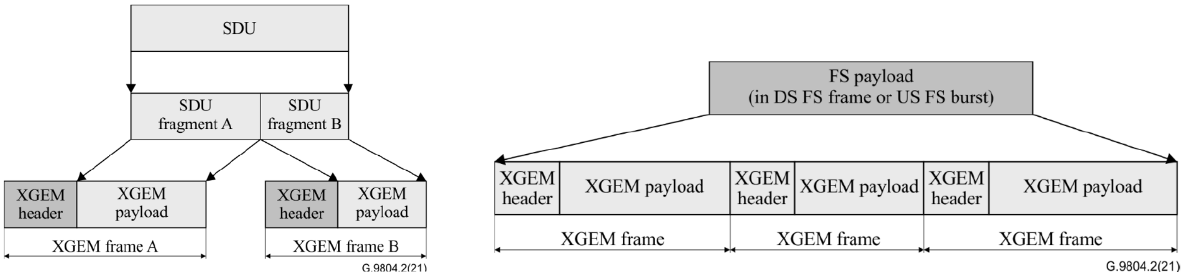

Figure 13 – Fragmentation at SA Layer,XGEM Encapsulation in FS Payload

Source:*ITU*-G.*9804.2-Figure 9-4, Figure 9-1*

After XGEM encapsulation occurs, the XGEM frames are assembled into the Framing Sublayer (FS) payload. The FS payload, Figure 13 is simply a concatenation of XGEM frames. In the downstream, the number of XGEM frames in the FS Payload is dependent on the line rate and the PHY frame size. The PHY frame size is always 125µsec and in the downstream PHY frames are transmitted in a continuous stream. Therefore, as the line rate increases, the amount of data that can be transmitted in a PHY frame will increase accordingly. In the upstream, data is transmitted in bursts that can be smaller than the PHY frame, but the same scaling principle can be applied, i.e., as the line rate increases, the amount of data that can be transmitted in a given time period will increase accordingly.

6.2.1.2. Framing Sublayer

The framing sublayer is slightly different in the upstream versus the downstream.

6.2.1.2.1. Downstream FS Frame

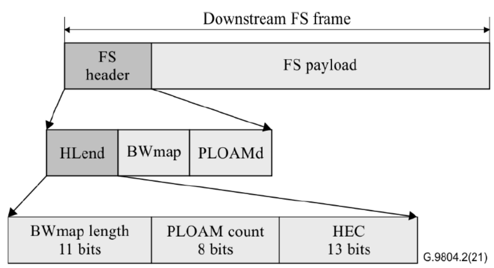

Figure 14 – Downstream FS Frame Format

Source:*ITU*-G.*9804.2-Figure 8-1*

The downstream FS frame contains the FS payload discussed above and an FS Header, Figure 14. The FS header carries several fields, but the BWMap is of particular interest relative to scaling ComTC to support 100Gbps operation, (BWMap contains structures that convey upstream grant opportunities to ONUs).

6.2.1.2.2. BWMap

The BWMap, Figure 15, contains a number of allocation structures, each containing a grant start time and grant size. Interpretation of these two values is directly related to the line rate of the PON and the PHY frame size of 125µsec. The Start Time field(16bits) potentially divides a PHY frame into 65536 "slots", the ComTC divides the PHY frame into 12150 "slots", each equal to one-time quanta (Q_0).

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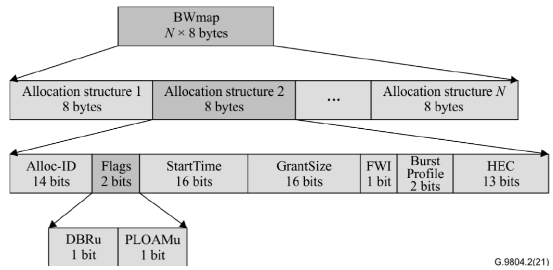

Figure 15 – Structure of the BWMap

Source:*ITU*-G.*9804.2 -Figure8-2*

Similarly, Grant Size is expressed as a value from 0 to 12149. The interpretation of GrantSize is dependent upon the line rate, so it follows that the interpretation of GrantSize will need to be adjusted for 100Gbps operation.

6.2.1.2.3. Upstream FS Frame

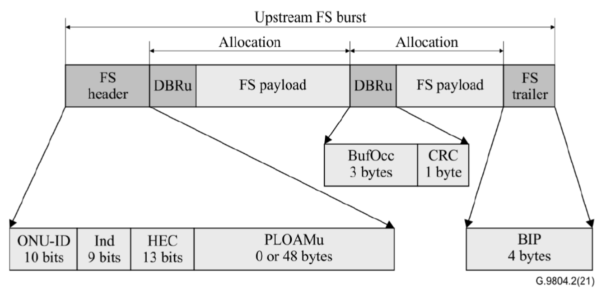

Figure 16 – Upstream FS Frame Format

Source:*ITU*-G.*9804.2-Figure8-5*

The upstream FS header contains the ONU-ID of the transmitting ONU, a series of Ind (ication) bits and the upstream PLOAM (PLOAMu) message. Because the upstream is a time division multiplexed system, the upstream FS frame, unlike the downstream FS frame, varies in size based on the Grant Size.

6.2.1.3. PHY Adaptation Sublayer

The PHY Adaptation sublayer connects the framing sublayer to the PHY layer by coding the FS frame and then encapsulating it with additional bit patterns necessary to ensure correct reception by the receiver.

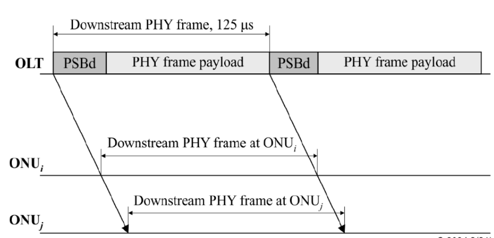

Figure 17 – ComTC Downstream PHY Framing

Source:*ITU*-G.*9804.2-Figure10-1*

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The downstream is a continuous stream of (125µs) PHY frames, Figure 17, containing a PSBd and a payload which is a bit stream after the FEC encoding, scrambling, and interleaving of the FS frame. In enabling 100Gbps operation, little would need to change in the PHY frame payload computation (aside from potential changes in the FEC), and these are not fundamentally related to the line rate. The PSBd contains data related to the PHY layer operation, timing, and alignment, and are not related to the line rate and not a concern in scaling to 100Gbps.

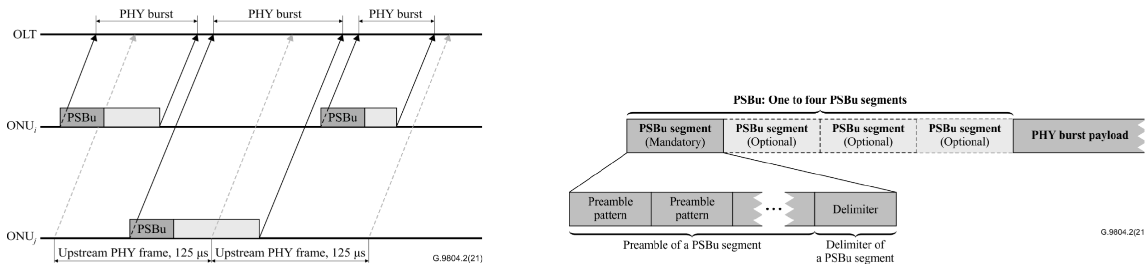

Figure 18 – Upstream PHY Framing, PHY Bursts and Preamble Format

Source:*ITU*-G.*9804.2-Figure10-5, 10-6*

The upstream PHY frame (Figure 18) is very similar to the downstream PHY frame. The key differences are replacement of the PSBd with a PSBu, the burst-nature of the upstream channel, and the upstream PHY burst varying in length based on the grant size issued by the OLT. These factors make the upstream PHY burst a key item for study when scaling to 100Gbps.

The PSBu provides a necessary function to enable burst reception at the OLT. It is the bit pattern used by the upstream receiver to perform clock data recovery, equalization, and automatic gain control.

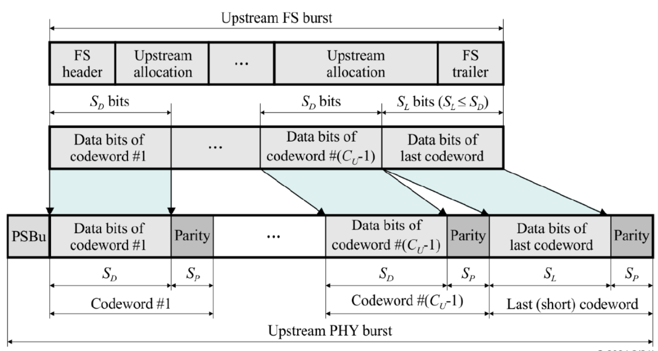

Figure 19 – Upstream FS Burst with FEC

Source:*ITU*-G.*9804.2-Figure10-11*

The PSBu can be customized on a per ONU basis to allow the operator to adjust for network and equipment characteristics. The PSBu length varies based on operator configuration but has a maximum length that is determined by the line rate (preamble in a PSBu segment can be up to 1000Q_0).

Another important factor in assessing the performance of PON is the Forward Error Correction (FEC). [GPON G.HSP] specifies the use of LDPC. The general function of FEC is achieved by encoding the data to be transmitted and adding parity bits to the outgoing data stream, Figure 19. An LDPC(17280, 14592) code is used for 50G PON, meaning that a codeword is 17280 bits long and includes 14592 bits of data and 2688 bits of parity.

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6.2.2. Scaling of GPON technology for CPON data rates

6.2.2.1. ComTC Changes to Support 100Gbps

Performance of PON can be evaluated on a few different dimensions. The major concerns are the impact of PON-specific overheads like FEC, framing, and physical layer overhead (preamble + guard time). Relative to scaling from 50G to 100G it will be important to identify the areas of ComTC that will need to be adjusted. It is important to state the assumption that the 125µsec frame size is immutable across GPON specifications, and that assumption will hold for CPON. Another aspect of the ITU-T series of PON specifications is the relationship of the line rate among the specifications, all derived from the SDH hierarchy, demonstrated in Table 12.

Table 12 – Relationship of Various PON Line Rates

PON Specification	Upstream Line Rate/ SDH Level	Downstream Line Rate/ SDH Level
G.984 GPON	1.24416Gbps = OC-24	2.48832Gbps = OC-48
G.9807 XGS-PON (10G PON)	9.95328Gbps = OC-192	
25GS-PON	24.8832Gbps = 10xOC-48	24.8832Gbps = 10xOC-48
G.9804 V.HSP (50G PON)	ρ_0 = 12.4416Gbps = 10xOC-24	
	2xρ_0 = 24.8832Gbps	
	4xρ_0 = 49.7664Gbps	

However, none of these line rates live up to the name given to each, especially when overheads are considered, e.g., XGS-PON is a “10G” PON, but the maximum user data capacity is approximately 8.8Gbps when FEC is enabled. This need not be the case for 100Gbps CPON or any future PON.

Specific parameters that need to be addressed to adapt ComTC for 100Gbps support are:

- Line Rate to Support 100Gbps User Data capacity
- BWMap Calculations
- Upstream Physical Layer Overhead Parameters

6.2.2.2. Line Rate

The main contributor to reduced data capacity is FEC coding (added parity bits) and physical layer overhead. To simplify the current study, framing overheads will be ignored, but an analysis attempting to achieve 100Gbps user capacity should take framing overheads into account.

The literature is rich with proposals and specifications for FEC intended for use in 100Gbps communication systems. E.g., the [OpenZRMSA], specifies OFEC at a coding rate of (4096,3552). While not proposing coherent transmission, Nokia has demonstrated 100Gbps PON, [FLCS PON], using PAM4 and FEC based on the EPON LDPC (17664, 14592). Since CPON is yet to make a FEC choice, we adopt the [Nx25G-EPON] FEC for analysis. This uses a codeword length of 17,664 bits with 14,592 information bits and 3,072 parity bits.

A simple calculation shows that the FEC overhead is: $FEC\ Overhead\ \% = \frac{3072}{14592} \times 100 = 21\%$

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To achieve 100Gbps of user data capacity, the nominal line rate would need to be at least 21% higher than 100Gbps, or at least 121Gbps. For the purpose of further study, we propose a nominal line rate of 10 times the ComTC fundamental line rate of 12.4416Gbps.

In other words, $\phi = 10$, $\rho_0 = 12.4416Gbps$

such that the nominal line rate for 100Gbps CPON might be $\rho_0\phi = 124.416Gbps$.

This is an option for further study as CPON is expected to be able to scale to higher rates such as 200Gbps, 400Gbps, etc.

7. Challenges and Future Considerations

This section discusses other related considerations to scaling the current EPON and GPON technology to the CPON technology.

7.1. FEC Evolution & Comparison

Forward error correction has been a powerful tool in the cable industry for many years. In fact, perhaps the single biggest performance improvement in the DOCSIS 3.1 specifications was achieved by changing the FEC (previously Reed-Soloman) to a new coding scheme with improved performance: low-density parity check (LDPC). Similarly, FEC has also become an indispensable element for high-speed optical transmission systems, especially in the current coherent optical transmission age. Since this is the first "marriage" of coherent and PON technologies, let's review current FEC usage in these two fields.

Table 13 – FEC in Optical Communication Links

HD: hard decision SD: soft decision	Coding overhead rate	Net coding gain (NCG) dB @10E-15	pre-FEC BER threshold
GFEC (HD)	6.69%	6.2	8.0E-5
EFEC (HD)	6.69%	8.67	2.17E-3
100G: Staircase FEC (HD)	6.69%	9.38	4.5E-3
200G: oFEC (SD)	15.3%	11.1 for QPSK 11.6 for QAM16	2.0E-2
400G: cFEC (SD)	14.8%	10.4 for QPSK 10.8 for QAM16	1.22E-2

On the coherent side, CableLabs adopted Hard-Decision (HD) Staircase FEC at 100Gbps, achieving an NCG of 9.38dB with pre-FEC BER of 4.5E-3, verified in the P2P Coherent Optics Interoperability Event. At 200Gbps, openFEC (oFEC) with NCG of 11.1dB for QPSK and 11.6dB for 16QAM is used in CableLabs' P2P Coherent Optics PHYv2.0 Specification, suitable for various scenarios. This oFEC was also standardized for metro applications by Open ROADM. For 400G, OIF adopted cFEC with inner Hamming and outer Staircase codes. The 400G IA offers NCG of 10.8dB and pre-FEC BER of 1.22E-2 for dual-polarized 16QAM, tailored for DCI. Table 13 summarizes standardized FEC performance in coherent optical fiber transmission systems.

On the PON side, the evolution of FEC has seen several advancements over time. The first generation of FEC for PONs were based on Reed-Solomon (RS) codes (255, 239), which offer good performance at low bit error rates (BER), Figure 20. As the demand for higher data rates and the corresponding link budgets in PONs has increased, the need for more powerful FEC has also increased.

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At 10G era, RS code moves to RS (255,223) and the truncated form (248, 216) with the NCG to 7.1dB. Second-generation FEC for PONs are based on LDPC codes, which offer significantly better performance than RS codes at high BERs. The [Nx25G-EPON] standard has adopted high-performance, hard-decision (HD), LDPC FEC with a BER threshold of about 1E-2 and a rate of 0.849 and 9dB of coding gain [DSP 50G].

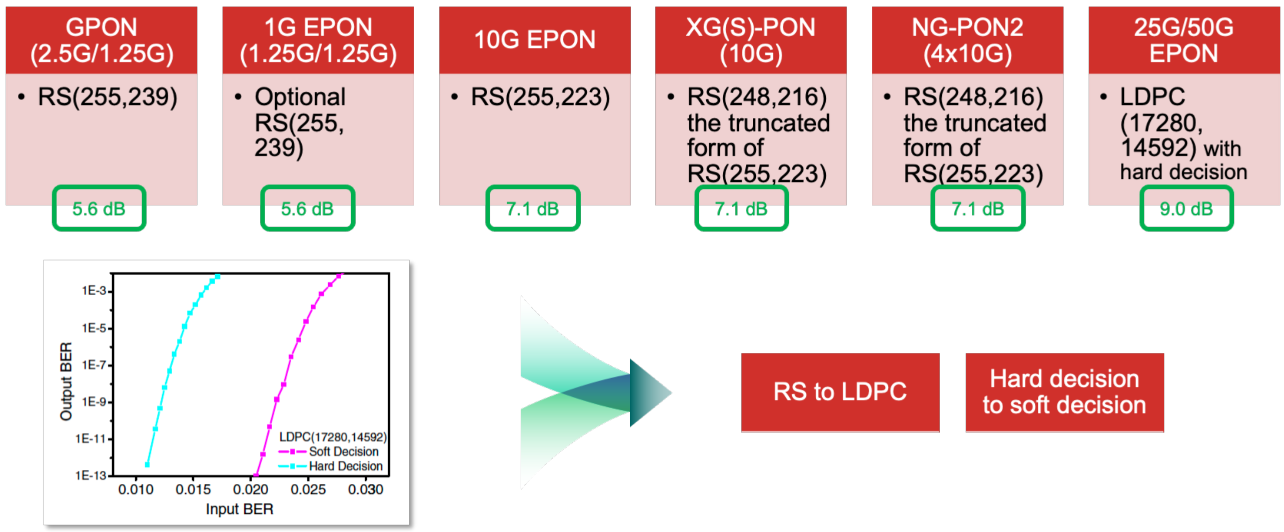

Figure 20 - FEC Evolution in PONs

In 50G and beyond PON, the link budget is more challenging to achieve. Therefore, soft-decision (SD) FEC is preferred to fully exploit the DSP function because SD FEC uses the full information of the received signal to make decisions about whether or not there is an error. This allows SD FEC to correct more errors than HD FEC, which can help to improve the link budget. Flexible FEC code rate has also been proposed to allow the OLT to choose the FEC code rate between 0.733 to 0.889 that is best suited for the current channel conditions [DSP 50G]. This can help to improve the BER and achieve higher throughput.

So, what kind of FEC should CPON choose? The requirements include being able to provide enough NCG to meet the different link budget requirements in CPON applications. The industry is currently considering how to leverage FECs that are already in use, especially the LDPC FEC for PONs. The LDPC FEC from [Nx25G-EPON], 25G-PON MSA, and [GPON-G.HSP] has been shown to be effective in other PON standards, only small changes are needed for the existing chip design and the compatible operation with PMD and MAC layers.

7.2. Channel Bonding

In [Nx25G-EPON], the latest evolution of EPON allows for 25G, 50G and potentially 100G capacities by introducing the concept of channel bonding. This strategy has already found utility in the cable industry through DOCSIS, which now has proven the channel bonding in multiple versions of DOCSIS. Channel bonding in EPON facilitates the aggregation of multiple 25G wavelengths to increase throughput. An ONU could be enabled to both transmit and receive data at a rate of 100G by aggregating four 25G wavelengths. Channel bonding serves as a mechanism for augmenting the speed of the next generation PON in a gradual manner, thereby extending the network's operational longevity. [Nx25G-EPON] specifies a simple and efficient channel bonding method for dynamic bonding of multiple channels. The

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MCRS, see 6.1.1.1, enables multiple MACs to interface with multiple xMIIs. This bonding method is controlled by the OLT scheduling and does not require any explicit provisioning or configuration. Under a channel-bonded approach, the dynamic bandwidth allocation (DBA) functions will need to orchestrate upstream transmissions across one or more wavelengths simultaneously.

The question for CPON technology is if we start with a single carrier or multiple subcarriers with channel bonding enabled. [Nx25G-EPON] can accommodate new PMDs with different characteristics. E.g., A single carrier TDMA PON architecture with 100Gb/s line rate or an architecture where each ONU can send and receive on multiple sub carriers. Currently [GPON-G.HSP] does not have support for Channel bonding. For CPON, we continue to analyze, investigate and debate the path forward. Enabling support for channel bonding from day one even if we choose to have a single carrier looks to be prudent so that next generation of CPON technology could easily build off of that base capability. Enabling channel bonding is an easy way to future proof the MAC layer of CPON allowing for easy extensibility.

7.3. Single Carrier vs Digital Sub-carrier

There are two potential options for CPON– conventional single carrier (SC) or digital sub-carrier (DSC) PONs, Figure 21. SC is the most common type of PON and uses a single wavelength to transmit data to and from multiple ONUs. The data is divided into time slots, and each ONU is assigned a specific time slot to transmit and receive data. DSC is a newer type of PON that uses two or more frequency bands in digital domain over a single coherent transceiver to transmit data to and from multiple ONUs. The data is divided into time slots and frequency bands, and each ONU is assigned a specific time slot and frequency band to transmit and receive data.

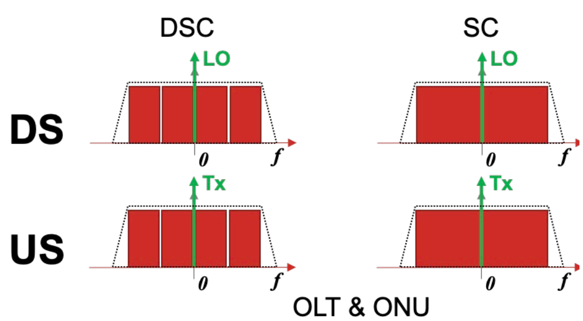

Figure 21 – Spectral Illustration of DSC and SC

The comparison between DSC and SC implementations in CPON presents distinct advantages and trade-offs. DSC offers several benefits, such as the reduction of burst overhead in upstream transmission for time-based sources of overhead. By allowing bandwidth trading, DSC facilitates additional link budget while maintaining overall capacity. It introduces the potential to employ sub-carriers for individual customers/services, enhancing network flexibility. However, there are notable concerns associated with DSC. It is anticipated that DSC implementations might lead to a reduction in nominal transmission (Tx) power from increased peak-to-average-power (PAPR), thus affecting the link budget by a magnitude of 3dB or more. DSC entails increased complexity, including subcarrier frequency and power control, as well as the need for tracking laser phase noise.

SC technology offers distinct advantages, it simplifies the achievement of the target link budget, as it avoids the PAPR loss inherent to multi-carrier approaches. Additionally, excess bandwidth can be exploited for power enhancement through shaping, contributing to improved performance. Seamless

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integration of SC modulation with existing MAC layers eliminates compatibility concerns. However, SC modulation faces its own set of challenges. Its lack of flexibility restricts the physical division of customers or services and the extension of reach. SC modulation introduces increased burst overhead stemming from time-based sources of overhead.

For system level design, the integration of Semiconductor Optical Amplifier (SOA) amplification, (external or integrated at the OLT), and potential low-cost implementation of Silicon Photonics, introduce additional factors that warrant consideration in the selection of the most suitable modulation technique for specific architectures and operational demands. Balancing these benefits and challenges is crucial to harness the long-term potential of CPON while addressing current market demands and infrastructure readiness.

7.4. Other challenges

The transition from legacy PON networks needs to be managed and operational systems need to be adapted to the new CPON technology. For EPON, the SIEPON specifications enable interoperability at the PHY and MAC layer between the OLT and ONU. This system-level and network-level standard, allows interoperability of the transport, service, and control planes across multiple vendors. Operators have built back-office software tools to provision services on the PON network on top of these 802.3 ah/av/ca, SIEPON and DPOE technologies. This is a fair amount of investment/expertise that operators may like to preserve. They also would like the ability to provision services across different types of PON networks and perhaps even other access networks using the same/similar provisioning systems.

On the GPON side, OMCI is common to the various iterations of GPON technology and other industry bodies, (such as the BBF), support these technologies with test plans and other work related to making the equipment interoperable. For any new technology, as the PHY matures many of the interoperability issues come at the PLOAM layer or at the OMCI layer. Work needs to be done for the CPON technology as well to allow for interoperability. This includes defining common OMCI messaging, third party testing, etc.

Deploying the fiber infrastructure is by far one of the biggest investments for an operator. New PON systems thus must be compatible with the existing ODN, which may include the trunk fiber connections between hub site to remote fiber nodes. This minimizes infrastructure costs and enables a non-disruptive migration toward CPON deployments. Three forms of coexistence are required for CPON systems: coexistence with IM-DD (legacy) PON systems, coexistence with P2P DWDM systems, and coexistence with other CPON systems (aka CPON stacking). Coexistence of CPON systems with other PON and DWDM systems is essential for operators to be able to migrate to CPON without having to replace their entire fiber infrastructure and deploy CPON systems in a variety of network scenarios.

8. Conclusion

As the PON evolves toward a data rate of 100Gbps or higher, PON technology based on coherent optical technology is a very promising solution due to its performance and potential. The cable industry is working towards developing new CPON technology for use in its networks. CPON is a fundamental change to physical layer, with the transmission technology moving from the IM-DD technology to coherent optical technology. The CPON technology will solve for not just for access network applications but also for transport applications like backhaul.

The new CPON PHY layer will need a supporting MAC layer to build a complete solution. We propose both a GPON based MAC layer and an EPON based MAC layer. This approach enables quicker time to market by implementors by reusing large digital logic components from previous implementations. It

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also allows operators who are already invested in either GPON or EPON to reuse a lot of the provisioning and back-office systems. This paper analyzed each of the EPON and GPON technologies and got an understanding of the EPON stack (MCRS, PCS, PMA) as well as the GPON stack (ComTC Service adaptation, framing and PHY adaptation layer).

EPON technology can be scaled to 100Gbps speeds by using a couple of different options. With multiple subcarriers approach, CPON technology can use 4 subcarriers, each at 25Gbps and use the EPON MAC layer as is. If we go down the single carrier approach, the MAC implementation will need to change to handle higher speeds, by increasing the MAC data rate to 100 (from 25Gbps today) which means increasing the xGMII clock by 4 times to 1.5625GHz. Another option is to design a new xGMII, with a larger bit width to support 256-bit transfers.

On the GPON side, the technology can be scaled to 100Gbps speeds by choosing a nominal line rate of 10x the ComTC fundamental line rate of 12.4416Gbps. Many of the other framing formats remain unchanged from the latest GPON technology. From this analysis we can prove the feasibility of both technologies, that they can work /scale for CPON data rates.

The choice of FEC is a big decision for the technology development, with many choices from Coherent and PON technology. The industry is currently considering leveraging the FEC that has already been developed, the LDPC FEC from 802.3ca, 25G-PON MSA, and G.HSP (all using the same mother code) has been shown to be effective in other PON standards, and only small changes are needed for the existing chip designs and compatible operation with PMD and MAC layers.

We also recommend the technology support a data rate of 100Gbps traffic (vs. a 100Gbps line rate target which only obtains a lower user data rate after FEC overheads). The 100Gbps goal is only a starting point, and the CPON technology can scale this further (to 200/300/400Gbps and beyond) to accommodate service targets for the future. As these specifications are developed the next generation requirements needs to be thought through, to allow for smooth evolution of CPON generations.

Abbreviations

ASIC	Application Specific Integrated Circuit
bps	bits per second
CPON	Coherent Passive Optical Network
DPoE	DOCSIS Provisioning of EPON
DSP	digital signal processing
EPON	Ethernet Passive Optical Network
FTTH	Fiber to the Home
FTTP	Fiber to the Premise
FEC	forward error correction
HD	Hard Decision
GPON	Gigabit-capable Passive Optical Network
LDPC	Low Density Parity Check
MAC	Medium Access Control
MCRS	Multi-Channel Reconciliation Sublayer
NCG	Net coding gain
ODN	Optical Distribution Network (ODN)

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OLT	Optical Line Terminal
ONU	Optical Network Unit
OAM	Operations, Administration, and Maintenance
PCS	Physical Coding Sublayer
PHY	Physical Layer
PSB(d/u)	Physical Synchronization block. (downstream or upstream)
PMA	Physical Media Attachment
PMD	Physical Medium Dependent sublayer
P2MP	point-to-multipoint
WDM	Wavelength division multiplexing
xGMII	(1/10/25/50Gbps) Media Independent Interface

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