Next Generation PON Technologies: 50G PON and Beyond (Invited)

Derek Nesset
Ipswich Research Centre
Huawei Technologies
Martlesham Heath, Ipswich, UK
derek.nesset@huawei.com

***Abstract*—In recent years, network operators worldwide have been upgrading their fiber-to-the-home networks from Gigabit-class PON systems to 10G-class. Naturally, the industry has also been working on the next evolution step for PON systems beyond 10G. At the ITU-T, this next step is defined by the Higher-Speed PON systems operating at 50 Gbps line rate. This paper reviews the standardized 50G-PON system and related technologies and what might come next for optical access.**

Keywords*— *optical access networks, passive optical networks, fiber-to-the-home

I. Introduction

With the increasing demand for high bandwidth services, copper-based broadband worldwide has been gradually replaced by fiber-based networks. Such networks are typically built on passive optical networking (PON) technologies whereby a single head-end unit can serve multiple end points over a tree-like fiber topology. In the early years of this millennium, the primary PON technologies deployed were predominantly of the Gigabit-class i.e. Gigabit-PON (GPON) [1] from the ITU-T or Ethernet-PON (EPON) from the IEEE [2]. Since about 2015, network operators have been upgrading their PON deployments with 10G-class technologies such as XGS-PON [3] from the ITU-T. There are currently estimated to be in excess of 800 million FTTH subscribers worldwide [4] and analysts expect that 30 million 10G-PON ports will be shipped in 2023 [5].

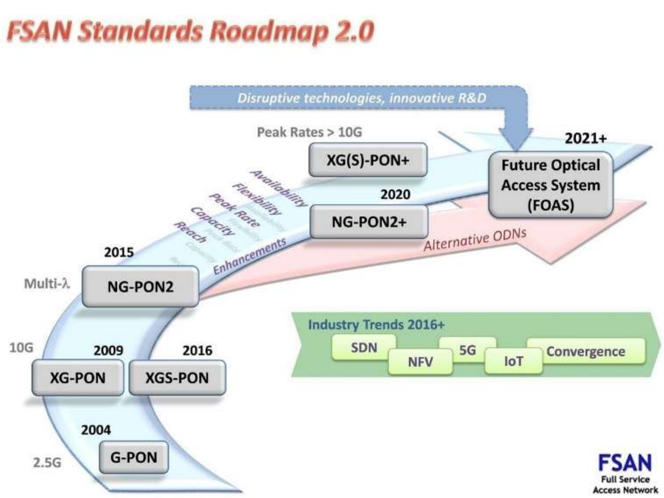

Fig. 1. FSAN Standards Raodmap 2.0

Just around the same time as the rollout for 10G-class PON was taking off, standardization bodies began to consider what comes next after 10G. Network operators in the FSAN forum developed their PON Roadmap [6] calling for beyond 10 Gbps PON in the ~2020 timeframe (Fig. 1). In the ITU-T, a study was initiated in 2016 to consider beyond 10G PON technologies as called for by the network operators in FSAN. This resulted in a document (G.Sup64) that reviewed the most promising options [7]. Following this initial study, it was agreed, after much debate, that the next ITU-T PON standard should be based on a 50 Gbps line-rate. A 25 Gbps line rate was also considered but, ultimately, rejected as it did not meet the ≥4x capacity increment between PON generations that is demanded by those network operators deploying PON at large scale.

In this paper we review the 50G-PON technology defined by the ITU-T in the G.9804.x Series of recommendations [8] and discuss what might be the next PON technology beyond 50G-PON.

II. 50G-PON Requirements

When considering the specification of a new PON technology, standards development organizations such as the ITU-T usually start with the network operator requirements. For 50G-PON, these are captured in the ITU-T recommendation G.9804.1 [9] first published in 2019. Once the common requirements satisfying network operators active in the ITU, including the largest deployers of such systems, have been agreed then the standards delegates can start to flesh out the technical details on how to meet these requirements. There is already some confidence about what is broadly feasible based on the earlier study captured in G.Sup64 [7] but there is still much work to do to converge on the final recommendations.

Among the highest priority requirements are those relating to the compatibility of 50G-PON with the already deployed fibre infrastructure and systems. Given the massive investments made to deploy PON optical distribution networks (ODNs), network operators will want to reuse the fibre plant for subsequent upgrades to their PON systems. In practical terms, this means compatibility with the loss budgets and fibre distances of the deployed ODNs. Loss budgets in the range of 28 dB to 35 dB have been specified for previous PON systems such as GPON and XGS-PON. For 50G-PON, initial priority was given to compatibility with class N1 (29 dB) and C+ (32 dB) ODN path losses. While fibre distances up to 40 km have been specified

978-3-903176-54-6

for earlier PON systems, 20 km class ODNs are much more common. Hence, a priority was given to the 20 km differential distance class for 50G-PON.

Compatability with previous PON systems generally means that 50G-PON can coexist simultaneously on the same ODN as the previous PON system. This is important for network operators as it allows for a progressive migration of subscribers from the older system to the new one. Wholesale swap out with forced migration of subscribers is highly undesirable from both the operational and customer experience perspectives. In general, coexistence is facilitated by the wavelength plan with systems coexisting through wavelength division multiplexing (WDM). Practically speaking this means locating the respective signals in regions of spectrum that are not occupied by previous PON system generations. Wavelength bands need to be allocated to both the downstream and upstream wavelength channels respectively. Sufficiently large guard bands will also have to be allocated to enable physical separation of each wavelength channel with good isolation, considering the practical limits of, for example, thin film filters (TFFs) in bidirectional optical sub-assemblies (BOSAs). The optical spectral bands selected for 50G-PON will also need to be amenable to the transmission of 50 Gbps signals over 20 km fiber distances with simple (low cost) transmitters such as directly modulated lasers (DMLs) and electro-absorption modulated lasers (EMLs).

The primary purpose of a new PON system generation is to meet the ever growing demands for bandwidth. Therefore, network operators place a high importance on the usable capacity that can be marketed to subscribers. With, at least, a fourfold capacity upgrade being a key demand for a new generation of fibre access system to be deployed at a large scale, network operators placed a requirement for at least 40 Gbps usable capacity for the 50G-PON downstream link. This leaves about 20% of the link bandwidth for forward error correction parity bits and PON framing overheads.

In addition to higher capacity, new services place additional requirements on the underlying access network. In particular, latency has become a critical parameter in applications such as mobile xHaul and advanced video (e.g. AR/VR). In anticipation of such service requirements, network operators have requested that 50G-PON supports low latency features to enable a true multi-service access network. There is little that can be done in the physical layer of the PON but low latency may be enabled by new TC-Layer functionality as we will see in the next section.

III. 50G-PON Transmission Convergence Layer

The Transmission Convergence Layer (TC-Layer) in ITU PON systems (see Fig. 2) is the engine that handles the key functions of the Time Division Multiple Access (TDMA) protocol. Generally speaking, the higher-level Service Adaptation and Framing Sublayers are largely unchanged in 50G-PON compared to previous ITU PONs. These layers handle aspects such as encapsulation and multiplexing of user data and construction of the PON framing which work fairly similarly across the different generations of PON.

For the Higher-Speed PON series of recommendations, of which 50G-PON is the first instance, a Common TC-Layer (ComTC) was defined [10]. This was an acknowledgement that the PON TC layers have a high degree of functional similarity across PON generations. Previous ITU PON standards had their own dedicated, and slightly different, TC Layers

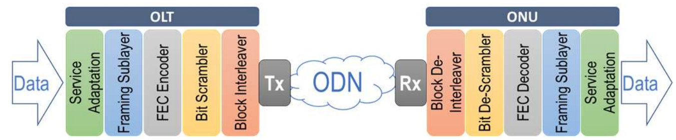

Fig. 2. 50G-PON Downstream Path TC Sublayers

A key aspect of the ComTC for 50G-PON is the high gain Forward Error Correction (FEC). With the increased bit-rate of the 50G-PON, compared to previous ITU PON generations running at 10 Gbps or less, comes a worsening of the receiver sensitivity. However, the loss budget of the deployed ODNs is fixed so there are two possible solutions to close the link at 50 Gbps. Firstly, the transmitter launch power could be increased, but there are limits to the power that can be launched considering eye safety, fiber non-linearity and transmitter cost/size/complexity. The second solution is to improve the receiver sensitivity, which can be done by improving the underlying optical receiver technology and through higher FEC gain. The ComTC can help with the latter by exploiting more powerful codes made possible through advances in the power of CMOS electronics. For 50G-PON, a Low-Density Parity Check (LDPC) code is employed instead of the conventional Reed-Solomon (RS) codes. Specifically, LDPC(17280, 14592) is used for the 50 Gbps downstream signal with a code rate of 0.844. A BER = 1×10^{-2} coming from the physical layer may be corrected using hard-decision decoding to better than 1×10^{-12} as required for the service layers. Even higher input BER maybe handled in the event that soft-decision decoding is employed.

An additional new function in the ComTC for 50G-PON is the Block Interleaver in the downstream (Fig. 2). This anticipates the use of DSP-based equalizers at the ONU receiver and the correlated errors that may be induced. The block interleaver effectively mitigates these errors by bit interleaving across four consecutive code words [11].

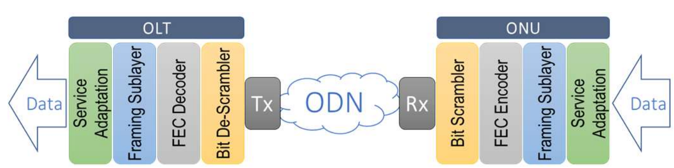

Fig. 3. 50G-PON Upstream Path TC Sublayers

Turning to the upstream TC-Layer (Fig. 3), the 50G-PON includes some additional features related to the assumption of DSP based receiver-side equalization. In particular, ComTC introduces a flexible multi-segment burst preamble that allows the OLT receiver to correctly detect bursts. Each segment may be optimized for one of the critical receiver functions such as amplitude recovery, clock recovery and equalizer adjustment. This feature is particularly useful during ONU activation, when the OLT does not know which ONU will respond at any particular instant during a quiet/ranging window. The ComTC allows for the OLT to define burst preambles with up to four segments, each with a different data pattern: either a standardized PRBS or a bespoke periodic bit sequence.

As mentioned in the requirements section above, low latency is critical to many emerging use cases for PON systems. Within the 50G-PON recommendations there are mechanisms supported by the ComTC to reduce latency. Firstly, 50G-PON supports Cooperative DBA (CO DBA) [12] whereby upstream scheduling information is provided by OLT-side external equipment, such as a BBU in a wireless transport system. This scheduling information acts as a time varying input to the OLTs dynamic bandwidth allocation (DBA) engine, enabling the OLT to apply targeted bandwidth allocations to service traffic volumes expected, in specified time intervals, by the client service equipment. The 50G-PON OLT also takes jitter and delay tolerance parameters as DBA inputs to enhance the bandwidth resource assignment capabilities and adapt them to the services.

In addition to the above enhancements in the ComTC, there are other new features to improve the efficiency, flexibility and security of the 50G-PON. These include an enhanced ONU activation procedure that speeds up the activation process and provides additional flexibility. Also, contention-based operation was introduced which improves upstream bandwidth utilization. In terms of security, new cryptographic algorithms were introduced to enable 50G-PON to satisfy the data security requirements in different geographic regions and in new applications. In addition to AES-128, 50G-PON can support cipher algorithms such as AES-256, Camellia-128, Camellia-256, and SM4. These additional cipher algorithms enable 50G-PON to address applications in new areas such as smart factory networks [13].

IV. 50G-PON Physical Media Dependent Layer

As might be expected by the significant increase in capacity, the Physical Media Dependent (PMD) Layer in 50G-PON is significantly changed compared to previous ITU-T PON generations operating at 2.5 Gbps and 10 Gbps. The necessary enhancements realize high 50 Gbps line-rates over the high PON ODN link budgets while exploiting low-cost components demanded in optical access applications. In particular, 50G-PON is the first to exploit DSP, enabled by advances in CMOS electronics, to overcome physical layer component and channel limitations.

A key early decision for any PON system is the wavelength plan. As mentioned earlier, this needs to consider many factors including; the available spectrum (considering coexistence requirements) and the wavelength dependent fiber channel impairments. With non-return-to-zero, on-off keying (NRZ-OOK) being the modulation method of choice (based on the simplicity and better sensitivity compared to PAM4, for example) the high baud-rate places stringent demands on the optical component bandwidths and limits the tolerable fiber chromatic dispersion.

The outcome of the ITU-T deliberations on the wavelength plan is shown in Fig.4. The downstream (DS) wavelength adopted is centered at 1342 nm which allows the upstream (US) wavelengths to occupy spectrum near the fiber dispersion zero wavelength region (US-A) or the negative dispersion regime (US-B). From a transmission perspective, this means that there is a good prospect that, simpler and lower cost, directly modulated laser (DML) based transmitters may be used at the cost-sensitive ONU side. The extra cost/complexity burden is placed on the downstream Tx which will, most likely, be based on EML-SOA devices to meet the power budget and overcome fiber chromatic dispersion (CD).

The upstream wavelength band options US-A and US-B allow so called “either/or” coexistence of 50G-PON with either GPON or XGS-PON. Thus, two generations of PON may coexist on the same ODN enabling, for example, replacement of GPON with 50G-PON and coexistence with XGS-PON or direct augmentation of GPON with a coexisting 50G-PON.

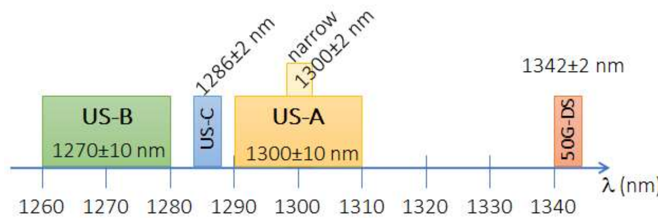

Fig. 4. 50G-PON Wavelength Plan

It may also be noticed in Fig. 4 that there is a narrow (4 nm) wavelength band option for the upstream centered at 1300 nm. This was introduced to ease isolation requirements for coexistence elements (WDMs) that may already be installed in the ODN. Furthermore, such an option may be useful in the event that a pre-amplified Rx is used. The narrow wavelength band option at 1286 nm is a more recent introduction in the first amendment of the 50G-PON PMD recommendation (G.9804.3 Amd1 [14]). This new wavelength band sits between the GPON and XGS-PON bands and allows for 3-generation coexistence of PON systems. This could be a valuable option for network operators that expect a long tail of GPON users in their ODNs. These narrow upstream wavelength band options provide flexible evolution paths for network operators, nevertheless, the 20 nm width options are generally expected to offer the lowest cost implementations as they allow for the potential use of uncooled ONU transmitters.

For the first time in ITU-T PON, the wavelength plan for 50G-PON has targeted the O-band for downstream as well as upstream. Even so, this still leaves some transmission challenges for the downstream signal in the 1342 nm band where fiber CD up to 77 ps/nm needs to be accommodated in 20 km ODNs. Furthermore, at the ONU, the best possible Rx sensitivity needs to be achieved within the constraints of the low-cost expectations for customer premises equipment. After some considerable ITU-T study, it was concluded that the best link design assumption is with NRZ-OOK modulation coupled with the exploitation of advances in electronic DSP to compensate for both link and optical component bandwidth limitations [15]. To achieve the high sensitivity Rx necessary for the high loss PON links an avalanche photodiode (APD) is required, however, commercial APD devices with good enough sensitivity are currently limited to ~25 Gbps. Rx-side DSP may be used to overcome the limited APD Rx bandwidth in addition to compensating for fiber CD induced inter-symbol interference (ISI). Enabling the use of 25G-class optical components for 50 Gbps NRZ, through the exploitation of DSP, can realize a lower cost solution and early market access for 50G-PON products [16].

With Rx-side DSP and 25G-class APDs handling the ONU part of the downstream link, there still remain challenges for the OLT transmitter. Firstly, the launch power requirements are approaching +10dBm for the C+ optical path loss class of 32 dB. Secondly, low chirp is necessary to keep the path penalty down and avoid even higher launch power requirements. Thus, electro-absorption modulated lasers (EML) integrated with semiconductor optical amplifiers (SOAs) become the primary OLT Tx solution by virtue of their low frequency chirp and high launch powers. Devices have already been reported in the literature [17] with performance enabling even E2 class link budgets of 35 dB to be reached.

For transmission in the upstream direction, the main challenge on the ONU side is to meet the low-cost expectations in optical access subscriber equipment. There are 3 line-rates specified for the upstream in 50G-PON i.e. 12.5, 25 and 50 Gbps. The wavelength plan (Fig. 4) facilitates the use of DML devices even at 50 Gbps. At 12.5 Gbps, it is expected that DML components derived from the 10 Gbps XGS-PON transmitter technologies can be used, even though the line-rate is higher, as the FEC gain is also higher for 50G-PON. The use cases for the 12.5 Gbps rate are likely to be those targeting relatively low-cost ONUs where a high degree of asymmetry in the data rate is acceptable. It offers only a small increment on upstream capacity compared to the XGS-PON system being deployed in massive volumes today.

It is anticipated that the 25 Gbps upstream rate might be a “sweet spot” for the 50G-PON deployments. The 2:1 ratio of downstream data rate to upstream is well suited to the needs of the majority of PON users. Such a rate also offers a significant service upgrade compared to previous generations of PON. Furthermore, the ONU launch power requirements are relatively modest, compared to 50 Gbps, which offers the prospect of uncooled operation with DMLs to further limit the cost and power consumption.

In the first amendment of the 50G-PON PMD recommendation [14] one of the main new additions was the 50 Gbps upstream line rate specification. This was considered lower priority by network operators for the first release of the 50G-PON standard, as the target symmetric rate applications were not necessarily in the high volume FTTx markets but in business, backhaul or some of the emerging PON applications. A key priority for 50 Gbps upstream was to enable the use of DMLs at the ONU. This means keeping the launch power as low as possible while still ensuring the OLT Rx is feasible without necessitating optical preamplification. Nevertheless, the launch power requirement ~7 dBm is still on the higher side and may, in the short term, require the use of cooled devices.

Of course, much of the above discussion about the upstream line-rates, the potential applications and what will be the most popular rate combination is speculative. Ultimately, it is the market that will decide and this will be driven by whether a strong business case can be made. Furthermore, there is still learning to be done concerning the technology and driving out costs of the more advanced components at these higher line-rates.

V. 50G-PON Prototypes and Trials

Even though the first full suite of 50G-PON recommendations were only published by the ITU-T in September 2021, already a report of carrier lab trials of 50G-PON prototype equipment by China Telecom was made at ECOC that same month [18]. This 50G-PON prototype was built into a commercial PON system chassis and demonstrated several key features of 50G-PON showing the already significant progress towards real product implementations. The upstream line rate implemented was 25 Gbps as that was the maximum standardized upstream rate option at that time. The trial was run over an ODN with a 1:32 optical split and up to 10 km fiber distance. The reported results included ~40 Gbps of useful downstream service capacity with ~80 µs latency and a 21.5 dB ODN loss. In this prototype, the link budget was largely limited by the use of an EML rather than the necessary EML-SOA devices that meet the launch power requirement. As mentioned already, EML-SOA devices have already been reported [17] that meet the requirements for the 50G-PON OLT transmitter. The above lab trial was followed by a field trial of 50G-PON in a 5G small cell backhaul application scenario [19].

In another milestone, a 50G-PON field trial was reported in July 2022 in a live network setting at Swisscom [20]. Similar trials have now been conducted by several operators in different countries, demonstrating the considerable interest in 50G-PON as the next mainstream evolution step for ITU-T standardized PON. These include the first live trail in the Middle East [21], the first trail in Malaysia [22] and testing by Open Fiber in Italy showing coexistence of 50G-PON with XGS-PON [23].

There is clearly good progress towards 50G-PON commercialization with prototype systems already in the hands of network operators. The underlying technologies are also demonstrating advancement towards maturity, including many of the key opto-electronic and electronic components [24]. Given this background, it is little surprise that the first announcements of 50G-PON products have recently been made. At MWC 2023, Huawei launched the industry’s first commercial 50G PON solution [25]. In addition, Huawei also announced the first Passive Optical LAN (POL) prototype targeting the campus network application [26].

VI. Future Directions for PON

In Q2 of SG15 in the ITU-T a study has recently been initiated into what could come next after 50G-PON. This new project is directed at publishing a supplement on Very High Speed PON (G.SupVHSP), very much in the same spirit of G.Sup64 which preceded the start of the Higher Speed PON project at 50 Gbps line-rate.

The scope of the G.SupVHSP supplement includes the system requirements and characteristics of optical transmission above 50 Gbps per wavelength. It will address the required system capacity and coexistence requirements as a key driver of the wavelength plan. The challenges of transmission above 50 Gbps in optical access, including any trade-off between capacity and link power budgets, will be explored. Candidate technologies, including TDM, WDM, FDM among others, will be reviewed against the identified requirements.

There is a growing consensus that ~200 Gbps could be the next major evolution step for ITU-T PON. This fits well with the long standing ≥4x multiplier trend for capacity growth per PON generation. Thus, researchers have been motivated to explore a range of technical solutions to achieve these 200 Gbps rates over link budgets compatible with already deployed ODNs.

100 GBaud, PAM4 has been demonstrated [27] using PAM4 modulation of DMLs and SOA pre-amplified reception. The poor Rx sensitivity of PAM4 had to be compensated using Raman amplification in the >29 dB link. Raman amplification might be considered somewhat exotic for low cost PON applications. In [28] the PAM4 sensitivity penalty was overcome through the use of coherent reception. However, the polarization diversity coherent Rx used in the latter case might be too complex for the cost sensitive subscriber ONU. To cost reduce the ONU-side coherent Rx, the authors in [29] used a simplified structure with just one pair of balanced photodiodes and a single polarization Rx. Complexity is introduced at the OLT side (where costs are shared) through the use of Alamouti polarization/time coding. In the most recent demonstration we review here, the authors in [30] extend the use of Alamouti coded transmission to a real-time link experiment with hybrid time-domain/frequency-domain multiple access (TFDMA) 200G PON.

Crucial to the studies in G.SupVHSP will be the technical requirements and timescale for deployment of such systems. Will the drivers be the same as in the past (i.e. primarily upgrade to FTTH) or will there be new drivers with different requirements? We now see many new use cases emerging for PON as identified by the F5G ISG in ETSI [31] and the vision of Fiber to Everywhere. These use cases include campus networks, fiber-to-the-room (FTTR) and industrial applications. As ever, we also have the evolution of mobile networks with 6G expected around the 2030 timeframe. Potentially these applications will drive new requirements and the timeline for the generation of PON beyond 50 Gbps?

VII. Conclusions

The evolution of ITU-T PON systems from GPON through to XGS-PON and, in future, to 50G-PON has been reviewed. Important considerations for PON evolution such as coexistence and compatibility with the legacy fiber infrastructure have been highlighted. The key features of both the TC and PMD layer in 50G-PON have been discussed. Furthermore, the technology progress of 50G-PON has been demonstrated with reference to advanced component development and carrier trials of system prototypes.

The challenges that have to be overcome to meet the low-cost expectations for PON equipment, especially in the FTTH application, have been reviewed. The particular role of DSP in 50G-PON to permit the use of lower cost components has been highlighted. 50G-PON will be the first DSP enabled PON system and is expected to be the mainstream evolution step for network operators beyond 10G-PON [5].

With 50G-PON standards now completed, and products anticipated in the next year or so, the industry is now considering the next PON step. Within the ITU-T, a new study has been initiated into VHS-PON which will explore the requirements and technologies for PON beyond 50 Gbps. Meanwhile, the research community is busy addressing the innovations necessary to realize a 200Gbps line rate PON.

Acknowledgments

The author gratefully acknowledges the experts in Question 2 of Study Group 15 in the ITU-T without whom there would be no 50G-PON recommendations to review. Furthermore, I thank colleagues in Huawei's Munich Research Centre for their continuing support of optical access standardization.

References

[1] "*Gigabit-capable passive optical networks (GPON)*," ITU-T G.984.x Series Recommendations, (2004)

[2] "*Ethernet in the First Mile (EPON)*", IEEE Std 802.3ah, (2004)

[3] "*10-gigabit-capable symmetric passive optical network (XGSPON)*," ITU-T Recommendation G.9807.1, 2017

[4] www.point-topic.com/post/global-broadband-subscribers-q3-2022

[5] "*Access Optics Market Forecast*", LightCounting, November 2022

[6] www.fsan.org

[7] "*PON transmission technologies above 10 Gb/s per wavelength*," ITU-T Supplement G.Sup64, 2018

[8] R. Bonk et al., "*50G-PON: The First ITU-T Higher-Speed PON System,*" in IEEE Communications Magazine, vol. 60, no. 3, pp. 48-54, March 2022.

[9] "*Higher speed passive optical networks: requirements*," ITU-T Recommendation G.9804.1, 2019

[10] "*Higher speed passive optical networks - Common transmission convergence layer specification.*", ITU-T Recommendation G.9804.2

[11] X. Liu, A. Shen, N. Cheng, Y. Luo, and F. Effenberger "*Performance Improvements in Bandwidth-Limited and Digitally-Equalized 50G-PON Downstream Transmission via Block-Interleaving over Four LDPC Codewords*," OFC 2021, paper M3G.6

[12] "*Optical line termination capabilities for supporting cooperative dynamic bandwidth assignment*", ITU-T Supplement , G.Sup71, 2021

[13] D. Zhang, Y. Luo and J. Jin, "*Highspeed 50 Gb/s Passive Optical Network (50G-PON) Applications in Industrial Networks*," 2022 IEEE 23rd International Conference on High Performance Switching and Routing (HPSR), 2022

[14] *"50-Gigabit-capable passive optical networks (50G-PON): Physical media dependent (PMD) layer specification Amendment 1",* ITU-T Recommendation G.9804.3 Ammendment 1

[15] M. Tao, J. Zheng, X. Dong, K. Zhang, L. Zhou, H. Zeng, Y. Luo, S. Li, and X. Liu, "*Improved dispersion tolerance for 50G-PON down-stream transmission via receiver-side equalization*," OFC 2019, paper M2B.3

[16] B. Li, K. Zhang, D. Zhang, J. He, X. Dong, Q. Liu, and S. Li, "*DSP enabled next generation 50G TDM-PON*," J. Opt. Commun. Netw. 12, D1-D8 (2020)

[17] R. Rosales et al., "*First Demonstration of an E2 Class Downstream Link for 50Gb/s PON at 1342nm*," ECOC 2020, paper Tu2J-5

[18] D. Zhang, D. Liu, D. Nesset, X. Wu and J. Ming, "*Carrier Lab Trial of a Real Time 50G-PON Prototype*," ECOC 2021, paper We3F.5

[19] N. Wang, J. Li, D. Liu, Y. Wu, J. Zhu, D. Liu, L. Bai, D. Zhang, H. Li, and B. Li , "*A Field Trial of 50G TDM-PON Based 5G Small Cell Backhaul*", OFC 2022 , paper Tu3F.2

[20] www.swisscom.ch/en/about/news/2022/07/11-neuster-glasfasertechnologie.html

[21] "*stc and Huawei accomplish the first 50G PON live trial in the Middle East*", 2 February 2023. www.huawei.com/en/news/2023/2/first-50gpon-live-trail

[22] "*TM teams up with ZTE to enable Malaysia's first 50Gbps fibre broadband experience*", 20 January 2023. malaysia.news.yahoo.com/tm-teams-zte-enable-malaysia-132159986.html

[23] "*Open Fiber Tests 50G-PON Technology*", 25 January 2023. telecomtalk.info/open-fiber-italy-tests-50g-pon-technology/659770

[24] "*Semtech Demonstrates World's First 50G Higher Speed PON Compliant Chipset at OFC 2023*", 7 March 2023 www.businesswire.com/news/home/20230307005458/en/Semtech-Demonstrates-World's-First-50G-Higher-Speed-PON-Compliant-Chipset-at-OFC-2023

[25] "*Huawei Releases the World's First 50G PON Commercial Solution for 10G All-Optical Access*.", 9 March 2023. telecoms.com/intelligence/huawei-releases-the-worlds-first-50g-pon-commercial-solution-for-10g-all-optical-access

[26] "*Huawei Launches Industry-First 50G POL Prototype for Next-Generation Wi-Fi 7 Campus Networks*.", www.bloomberg.com/press-releases/2023-03-02/huawei-launches-industry-first-50g-pol-prototype-for-next-generation-wi-fi-7-campus-networks

[27] D. Che, P. Iannone, G. Raybon, and Y. Matsui, "*200G Bi-directional TDM-PON with 29-dB*," ECOC 2021, paper-We4F.1.

[28] J. Zhang, J. Yu, K. Wang, W. Zhou, X. Xiao, J. Xiao, L. Zhao, X. Pan, B. Liu, and X. Xin, "*200-Gb/s/ λ PDM-PAM-4 PON with 29-dB power budget based on heterodyne coherent detection*," OFC 2019, paper Th3F.1.

[29] M. S. Faruk, X. Li, and S. J. Savory "*Experimental Demonstration of 100/200-Gb/s/λ PON Downstream Transmission Using Simplified Coherent Receivers*", OFC 2022, paper Th3E.5.

[30] Z. Xing, K. Zhang, X. Chen, Q. Feng, K. Zheng, Y. Zhao, Z. Dong, J. Zhou, T. Gui, Z. Ye, L. Li, "*First Real-time Demonstration of 200G TFDMA Coherent PON using Ultra-simple ONUs*," OFC 2023, PDP paper Th4C.4

[31] www.etsi.org/committee/f5g