Reusing Data Center Optics and Solutions for Beyond 25Gb/s PON: Is the Gap Really Bridged?

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Abstract: In this paper we will review the benefits as well as challenges to overcome in adoption of data center technologies for next-generation TDM-PONs.

1. Introduction

A Passive Optical Network (PON) is a network architecture that can provide high speed access to its users in a cost-effective way. The most commonly deployed PONs today are Time-Division-Multiplexed TDM-PONs using Non-Return-to Zero (NRZ) as the modulation format. TDM-PONs success depends largely on the pre-existence of mature high volume, low cost optical and electronic technologies, and components. Up till 10G this volume was driven by the Synchronous Optical Network/ Synchronous Digital Hierarchy (SONET/SDH) metro market where after enough cost erosion it was adopted for PON [1]. Data center networks (DCN) demand has driven 100 Gigabit Ethernet technologies based on 25 Gb/s NRZ lanes as standardized by IEEE 802.3bm in 2015 [2]. Large volumes of reduced cost 25G components are now readily available such as directly modulated lasers (DMLs), electro absorption modulated lasers (EMLs), avalanche photodiodes (APDs), transimpedance amplifiers (TIAs), as well as serial/de-serializers (SerDes) technology. This is the mature ecosystem 25G PON is leveraging currently [3,4].

2. 50G TDM-PON

The optical interface technology in DCN is predominately driven by advances in switch ASIC SerDes speeds due to decreasing CMOS node sizes. In 2017 IEEE 802.3bs standardized 200 and 400G using 26 Gbaud/s optical lanes based on Quaternary Pulse Amplitude Modulation (PAM-4). A 400G BASE DR4 was also defined at 53 Gbaud/s PAM-4 [5]. Physical layer Baud-Rate Sampling (BRS) Digital Signal Processing (DSP) is employed at the receiver side to mitigate penalties due to bandwidth limitations, non-linearities and dispersion. Various other DCN standards based on 53 Gbaud PAM-4 started to become available as well (802.3cd,cu,ck,db as well as 100G λ MSA), which technology currently is displacing 100G in data centers. An obvious choice therefore was to adopt this technology solution and adapt it for the next generation 50G TDM-PON. A first version of the 50G PON standard has been published recently in ITU-T G.9804 [6]. PON is very different from point-to-point DCN optical links in that reaches are typically much longer (up to 20 km) and the power budget is much higher (≥29 dB) [7]. Therefore, for 50G PON simple NRZ transmission has been chosen since it provides the best receiver sensitivity, making it easier to meet the stringent loss budget. Also, a stronger LDPC Forward-Error-Correcting (FEC) code with a pre-FEC BER=1e-2 has been accepted. Since the system will operate at 50 Gbaud and NRZ can be considered as the two most outer levels of a 50 Gbaud PAM-4 signal it is still very compatible with ~50Gbaud DCN DSP and SerDes technology. APD based receivers are still favorable for PON to meet the loss budget in a low power consumption cost-effective way. Even though 50 Gb/s capable APDs have been reported in literature [8] its low volume and reduced sensitivity compared to 25G makes them unattractive to be used in 50G PON for now. Therefore, 50G PON will still rely on 25G class APDs and will use DSP to ameliorate the penalty due its reduced bandwidth. 25G APDs will be deployed in high volume for 5G mobile and to a smaller extent 25G PON as well as for the 40 km data center interconnect (DCI) market (ER4 Lite). Another technical challenge with increasing the serial bitrate to 50G for PONs is the decreased chromatic dispersion (CD) tolerance since it is inverse proportional to the square of the bit-rate.

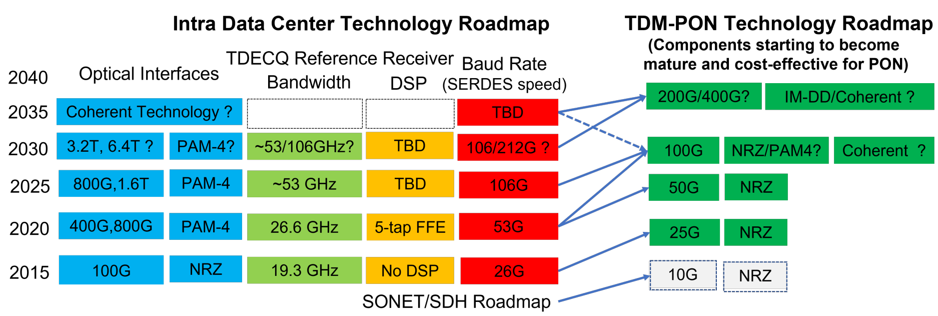

Figure 1: Technology Roadmap of Intra Data Center Technologies, where after enough cost erosion it is adopted for TDM-PON

For this reason, both the downstream (DS) as well as upstream (US) wavelength are chosen in the O-band in-line with 25G PON as well as DCN. The DS is located at λ=1342±2 nm with 0 to 77.1 ps/nm of fiber dispersion and for US at λ=1270±10 nm with 0 to -140 ps/nm (option 1) and at λ=1300±10 nm with -66 to 18.4 ps/nm (option 2) of fiber dispersion. Receiver side DSP is used to compensate part of the dispersion penalty. The adoption of DSP for 50G PON requires new quality tests, test patterns and quality parameters which means a substantial change from previous PON standards. To ensure physical layer interoperability of 50G PON equipment Transmitter and Dispersion Eye Closure (TDEC) testing has been proposed. This method to qualify transmitters has already been adopted in DCN where it was developed for NRZ in [2] and was extended to TDECQ for PAM4 [5]. TDEC/TDECQ is used to screen out transmitters that won't close the link for a worst-case channel in the field, so the reference receiver used to compute TDEC/TDECQ needs to be well defined. In DCN standards the TDECQ reference receiver is defined with a bandwidth of ½ the Baud-Rate (Nyquist bandwidth) and 4^{th} order Bessel filter roll-off using a 5-tap T-spaced FFE reference equalizer. For 50G PON in downstream a 13-tap T-spaced FFE reference equalizer was adopted, while in upstream 7-taps were agreed to relax requirements under burst-mode operation. In reality, the DSP of real-receiver implementations in DCN are much more powerful (many more FFE taps with DFE and/or MLSD) and NRZ is more resilient to impairment then PAM-4. The bandwidth of the TDEC reference receiver in 50G PON was set at 18.75 GHz to enable 25G class APDs. A transmitter with a larger TDEC value than 1.5 dB (maximum 5 dB) must transmit at a higher optical modulation amplitude (OMA) to be standards compliant. This flexibility in the specification enables more options for optical transmitter technologies without sacrificing interoperability, ensuring a more diverse and mature transmitter supply chain for 50G-PON. Cost effective transmitters for 50G PON can therefore be sourced from DCN transmitters technologies [9] and 50G EML based transmitters with high output power (up to 13 dBm) have already been demonstrated to meet the stringent PON power budget [10]. Although for most part we can rely on DCN technologies there is an important technology which is very PON specific (meaning we can't rely on mature pre-existence) which are burst-mode (BM) receivers for the upstream direction. To enable receiver side DSP in the upstream, a linear burst mode receiver (BMR) and fast converging equalizer will be needed. The design of a burst-mode TIA and CDR is quite challenging, however 50 Gbaud burst-mode receivers starting to become available in research [11].

2. 100G TDM PON and Flexible PON

A logical next step for 100G PON would be to switch the modulation format to 100 Gb/s PAM4 from 50 Gb/s NRZ since it achieves twice the data-rate at the same clock frequency and channel bandwidth. However, a disadvantage of PAM4 is that its signal amplitude is only 1/3 of a NRZ signal resulting in a theoretical optical modulation penalty of 4.8 dB for PAM4. Also, PAM4 requires more linearity reducing ER and OMA at the transmitter while the signal dependent multiplication noise of APD based receivers translates into closure of the top eye of a PAM4 signal. While the receiver DSP can provide partial mitigation, a penalty of ~9 dB was measured between 50Gb/s NRZ and 100Gb/s PAM4 using 25G APDs [12]. Moreover, since the spacing between voltage levels is tighter, it accrues more ISI than a NRZ bitstream at the same baud rate. This means it will be challenging to enable PAM4 for all ONUs on the ODN, especially for high loss and/or far away ONUs using current 50Gbaud DCN DSP and optical technologies. A practicable option could be to wait till the next generation ~100 Gbaud/s DCN technology becomes mature and low cost enough for 100G NRZ PON applications. DCN technology supporting 100 Gbaud/s PAM-4 for 800G and 1.6 Tbps are currently under active discussion and standardization in 802.3df and 800G pluggable MSA [13,14]. To meet the power budget for 100G NRZ PON a stronger FEC with input BER=2e-2 may be needed. At this point in time (2030 timeframe) ~50 GHz capable APDs might have enough performance [8] or alternatively a 50GHz PINs from DCN could be used and pre-amplified (SOA-PIN) for improved receiver sensitivity. Since 802.3df has an objective of 800G DR4/FR4 by means of PAM4 as well, chances are high that these components will become mature and cost effective in time for 100G NRZ PON. The decreased dispersion tolerance at 100G can be mitigated by carefully selecting the transmission wavelength, closer to the zero-dispersion wavelength and/or by reducing the chirp of the transmitter. Since PON only requires 1 wavelength each for up and downstream direction on the same fiber this is more feasible than DCN which at a minimum require 4 wavelengths on the same fiber, usually on a CWDM or LAN-WDM grid. Pre-existing wavelengths of already deployed PONs need to be considered to ensure coexistence. Stronger equalization adopted for 802.3df technology will also help with 100G PON to meet reach and power budget. Another way to extend the usage of Intensity-Modulated Direct-Detection (IM-DD) technology is to stack two or more wavelengths for increasing the overall line-rate beyond 50G on the PON. In IEEE 802.3ca [3] this has already been standardized for 50G PON by stacking two 25 Gb/s wavelengths. Since continuing doubling the line-rate typically results in significant performance penalties due to lower performing transceiver parts, stacking of two (or more) wavelengths can result in a better optical power budget compared to a single wavelength at twice the line-rate. For this we can also rely on DCN integration technology where it is very common to combine 4,8 or even more wavelengths in a single pluggable module. The DS line-rate of current standardized PONs is fixed. However, due to its point-to-multi point (PtMP) architecture, a PON is a well suited for benefiting from flexible line-rates [15]. One way of achieving 100 Gb/s in the downstream is by introducing flexible line rate modulation by changing the modulation format to 100Gb/s PAM4 for groups of optical network units (ONUs) if channel conditions allow [16]. Each ONU will only decode the FEC code-words (CWs) allocated to it. 50G NRZ and 100G PAM4 are a natural fit because they both are modulated at 50 Gbaud and therefore can use the same CDR(Clock and Data Recovery) as well as BRS DSP [17].

3. 100/200/400G Coherent PON

So far IM-DD based systems have been the preference for DCNs and PONs. It is a low-cost technology which has shown the ability to scale flexibly with the line rate while still meeting all the requirements. However direct detection systems suffer from limitations at high symbol rates related to poor receiver sensitivity, multi path interference (MPI) and RF-power fading due to chromatic dispersion. As access networks progress towards line rates beyond 100Gb/s, these shortcomings may make the continued use of IM-DD for PON impractical, especially for reaches up to 20km. Short reach DCNs might increase the Baud-rate or the number of lanes for 3.2Tb/s and 6.4Tb/s, however it faces the same challenges, especially for extended reaches beyond 2 km. Therefore, eventually coherent technology might be needed which, due to higher spectral efficiency, will result in reduced bandwidth requirements as well as better dispersion mitigation. A coherent interoperable standard (400ZR) was created by the Optical Networking Forum (OIF) for inter datacenter networks by transmitting 400G speeds at distances of at least 80 km [18]. Separately, in 2021 the open XR forum was created with the intent to develop 100/400G coherent pluggable modules for access and edge applications. Primary use cases will be mobile x-haul and extended reach, which is an inherent benefit of coherent. The technology comprises of Digital Coherent Optics (DCO) housed in a client-sized form factor. For now, this technology is still too costly, complex and power hungry for PON applications. However, the continued reduction in complexity, power consumption and cost of it and eventual introduction of short-reach coherent in the intra-data center [19] will further drive volumes of low-cost coherent technologies with the hope this can eventually be adapted for the next generation PONs as well. Adoption of coherent in PON will also solve the O-band spectrum crunch by using the C-band with effective dispersion compensation enabling reaches ≥20km.

4. Conclusions

We detailed the viability of (re-)using datacenter optical components and its DSP ecosystem for adoption as technology in next generation TDM-PONs

5. References

[1] Ed Harstead, et al., “Technology Roadmap for Time-Division Multiplexed Passive Optical Networks (TDM PONs)”, Journal of Lightwave Technology, Vol. 37, No. 2, Jan 15, 2019
[2] IEEE P802.3bm-2015 : IEEE Standard for Ethernet - Amendment 3: Physical Layer Specifications and Management Parameters for 40 Gb/s and 100 Gb/s Operation over Fiber Optic Cable
[3] “IEEE Standard for Ethernet Amendment 9: Physical Layer Specifications and Management Parameters for 25 Gb/s and 50 Gb/s Passive Optical Networks”, 802.3ca, 2020
[4] 25GS-PON MSA group, “25GS-PON Multi Source Agreement”, 2020, https://www.25gspon-msa.org
[5] IEEE P802.3bs (TM)/D2.0: Draft Standard for Ethernet Amendment: Media Access Control Parameters, Physical Layers and Management Parameters for 200 Gb/s and 400 Gb/s
[6] Recommendation ITU-T G.9804.3, “50-Gigabit-capable passive optical networks (50G-PON) : Physical media dependent (PMD) layer specification”,2021 https://www.itu.int/rec/T-REC-G.9804.3/en
[7] Doutje van Veen and Vincent Houtsma, "Strategies for economical next-generation 50G and 100G passive optical networks [Invited]," J. Opt. Commun. Netw. 12, A95-A103 (2020).
[8] M. Huang et al., “200Gb/s per lane Ge/Si waveguide avalanche photodiode”, in Proc. ECOC 2022, paper
[9] M. Theurer et al., “200 Gb/s Uncooled EML with Single MQW Layer Stack Design”, in Proc. ECOC 2022, paper
[10] N.Dubrovina et al., “Record High Power 13dBm Electro-Absorption Modulated Laser for 50G-PON”, in Proc. ECOC 2022, paper
[11] T. Gurne et al., "First Demonstration of a 100Gbit/s PAM-4 Linear Burst-Mode Transimpedance Amplifier for Upstream Flexible PON", in ECOC 2022 PDP (SC8), paper Th3A.1
[12] V. Houtsma and D. van Veen, “A real-time 25-50-100G Flex-Rate PON Implementation”, in ECOC 2022 Tu4C.2
[13] IEEE P802.3df 200 Gb/s, 400 Gb/s, 800 Gb/s, and 1.6 Tb/s Ethernet Task Force, https://www.ieee802.org/3/df/index.html
[14] 800G Pluggable MSA, https://www.800gmsa.com
[15] V. E. Houtsma and D. T. van Veen, ”Investigation of Modulation Schemes for Flexible Line-Rate High-Speed TDM-PON,” in J. Lightwave Technol., vol. 38, no. 12, pp. 3261-3267, 15 June15 (2020)
[16] R. Borkowski et al., ”Operator Trial of 100 Gbit/s FLCS-PON Prototype with Probabilistic Shaping and Soft-Input FEC,” in ECOC 2021
[17] N. Kaneda, et al., ”DSP for 50G/100G Hybrid Modulated TDM-PON,” in ECOC 2020, (2020)
[18] 400G ZR standard, https://www.oiforum.com/technical-work/hot-topics/400zr-2/
[19] Xiang Zhou, Ryohei Urata, and Hong Liu, “Beyond 1Tb/s Intra-Data Center Interconnect Technology: IM-DD OR Coherent ?”, Journal of Lightwave Technology, Vol. 38, No. 2, pp. 475 – 484, 2020