Commercial PONs have traditionally leveraged mature components from transport systems. Starting with 25G PON, the data center ecosystem will be leveraged. A strategy to accommodate higher speed at low cost is presented.
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Past and future perspective on TDM-PONs

TDM-PONs were invented in the late 1980s and, within a few years, questions were raised about the ability of TDM-PON to meet bandwidth demands. Expansion of capacity via multiple wavelengths was proposed for future PONs and so decades of WDM-PON research ensued. In the meantime, virtually all commercially deployed PONs have been of the TDM-PON variety, are highly cost-effective and have easily met capacity demands. Mass deployments started with BPON (622 Mb/s downstream, 155 Mb/s upstream) and EPON (1 Gb/s symmetrical), and were followed by GPON (2.488 Mb/s downstream, 1.248 Mb/s upstream). Deployment of 10 Gb/s class PONs (with 1, 2.488, or 10 Gb/s upstream) are currently ramping up.

The question this paper addresses is whether TDM-PON as a technology can continue to satisfy future bandwidth demands and, if so, how can they do so cost-effectively.

PON technology: the trickle-down effect and the new data center paradigm

During the past few decades, the success of TDM-PON has depended on the pre-existence of mature optical and electronic technologies. Volumes of these technologies were driven first by the long-haul market. After sufficient cost erosion these components were adopted by the metro market, driving volumes and maturation further, enabling their adoption by PON. This process required time; not only because the access market had lower price points, but also because these technologies had to be adapted for larger power budgets and burst mode operation.

This paradigm worked well: OC-12 and OC-48 (and STM equivalents) fueled BPON, EPON and GPON; OC-192 fueled 10G PON. However, in the 2000s, the 40G market fizzled out. When FSAN began standardization of a 40G PON in 2012, a mature 40G ecosystem did not exist and a multi-wavelength technology based on 10 Gb/s was selected. (One could argue that operators were premature in their estimate of the need for 40G capacity).

Figure 1: PON: a history of leveraging technologies matured in other domains
Data center technology found itself in a similar position. With no mature ecosystem for > 10 Gb/s Ethernet channels, the IEEE 802.3 community created a new family of 100 Gigabit Ethernet technologies based on 25 Gb/s channels. Eventually the insatiable demand for data center intra-connect capacity, much of it on single mode fiber, began to drive large volumes and reduced costs (to varying degrees) on 25G components such as DMLs, EMLs, APDs, TIAS and SerDes. This is the mature ecosystem that next generation 25G TDM-PON will leverage.

Is it possible to just plug these data center components into OLT and ONU transceivers? Of course not. PON applications will require new wavelengths, higher launch power from transmitters, and greater sensitivity from receivers. However, this is no different than the adoption, for previous PON generations, of components from long-haul and metro transceivers.

Figure 2: The PON “lag”: Each time, 3 technical challenges to overcome

With data center technologies now driving Ethernet towards 50 Gb/s and later 100 Gb/s channels, one can see a new paradigm emerging, where PON technologies follow data center instead of long haul/metro ecosystems.

**Leveraging the 25 Gb/s ecosystem for 25G TDM-PON**

The IEEE 802.3ca Task Force started work on the standardization 25G TDM-PON in 2016. (Two wavelength-stacked 25G PONs to realize 50G TWDM PON is also in scope).

The commercial success of 25G PON will depend on its ability to deliver 2.5x more bandwidth than 10G PON at a small incremental cost. This must be the guiding principle. When this happens, sometime after the year 2020, the market will flip from 10G PON to 25G PON. This is what gated the success of GPON: it was massively deployed once its incremental cost above BPON and EPON became small. If there is a large initial cost premium for 25G PON, it will sit on the shelf for years, just as 10G PON did.
The strategy to achieve low incremental cost is composed of the following elements:

- **O-band wavelengths.** Dispersion increases with higher bit rates. 25G PON downstream and upstream wavelengths need to be in the O-band to avoid large penalties or the need for dispersion compensation.

- **Simple NRZ transmission.** Higher level modulation schemes like PAM4 bring complexity and cost and come with significant power penalties.

- **No optical amplification.** 25 Gb/s has about a 5 dB power penalty compared to 10 Gb/s. To achieve a 29 dB (PR30 EPON, N1 class ITU-T PON) loss budget, and to avoid the cost of optical amplification, those 5 dBs need to come from a combination of higher launch power, improved receiver sensitivity and stronger FEC. This will be possible, but with little margin to spare.

- **Asymmetric 25G/10G ONUs.** Success is gated by a low cost ONU. Much cost can be avoided by using an uncooled 10G DML in the upstream direction. The most widely deployed PON technology in the world, GPON, proves that asymmetric bandwidth is perfectly adequate for high volume FTTH. Until the cost increment for a higher power 25G cooled DML diminishes, the more expensive 25G symmetric ONUs can be reserved for business services. (OLTs will, therefore, have to support both asymmetric and symmetric ONUs, the same as 10G PON OLTs).

**Figure 3: Strategy for 25G TDM-PON: simplicity for low cost**

**25G receiver based on 10G components.** 25G APDs have been developed for the relatively low volume 40 km single wavelength data center interconnect market. Therefore, the cost increment of 25G APDs versus 10G APDs may be significant and persist for some time. A powerful strategy, especially for use in the ONU, would be to use 10G APDs followed by electro-duobinary detection. This technique requires standardization of pre-coding at the transmit side. Alternatively, MLSE could be used to recover the 25G signal from a 10G receiver. However, this implementation would incur significant non-recurring engineering costs.

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25G PON wavelength plan and co-existence with legacy PONs

802.3ca has objectives for 25G PON to co-exist with both 10G PONs (1270 +/-10 nm upstream) and GPON (1310 +/-20 nm upstream). To accomplish this, there will be two choices for upstream 25G PON wavelengths: 1300 nm and 1270 nm for wavelength co-existence with 10G PONs (see Figure 4) and GPONs (see Figure 5) respectively. (It is also possible to support triple co-existence of 25G PON, XGS-PON and GPON by adding XGS-PON (see Figure 6), with 25G PON and XGS-PON sharing the same 1270 nm upstream wavelength in TDM fashion). Each upstream wavelength will have a +/- 10 nm tolerance to allow for uncooled lasers. The 25G downstream wavelength will be 1358 +/- 2 nm, and is assumed to be an EML laser.

The market is likely to favor the ONUs supporting GPON co-existence for two reasons:
- The addressable market for GPON upgrades will be much larger when 25G PON becomes commercially available.
- It will be more urgent to upgrade older GPON by a factor of 10x than newer 10G PON by a factor of 2.5x.
25G PON use cases

The strategy for 25G PON is to hit the FTTH cost target. However, that target might not be attained in the first years of product availability and residential bandwidth demand is unlikely to drive the need for >10G PON until at least 2025\(^3\). On the other hand, 25G PON is well suited to the following use cases:

- **Backhaul of deep fiber nodes**, for example G.fast DPUs in copper networks and DAA nodes in cable networks. Compared to 10G PON, the number of remote nodes that can be served by a single OLT port is increased by a factor of 2.5, with corresponding fiber savings.

- **Business services**. Due to various overheads, 10G PONs can provide at most an 8-9 Gb/s symmetric service. After overhead, 25G PON will have about 20 Gb/s capacity, and can deliver a committed 10 Gb/s business service, and still have another 10 Gb/s available for residential users on the same PON.

- **5G mobile transport**. Operators are preparing for the deployment of dense 5G radios. For mobile operators, these deployments will require a vast amount of new fiber connectivity. Alternatively, a converged FTTH network might be leveraged for lower costs and simpler operations for mobile backhaul, midhaul, and maybe even fronthaul transport. The higher bandwidth of 25G PON will be a better fit for this application than 10G PON. In fact, the expected timings for 25G PON wireline and widescale 5G wireless are well aligned.

- **5G, specifically fixed wireless access**. Many operators are considering 5G millimeter wave (mmW) as an alternative to the fiber drop used to connect homes in traditional FTTH networks. mmW is capable of delivering gigabit speeds but only over short distances. This leads to dense 5G antennas, and 25G PON might be the ideal way to provide backhaul/midhaul connectivity.

**Proposed roadmap to 50G TDM-PON**

50 Gb/s-based Ethernet channels are currently being standardized for 200 and 400 Gigabit Ethernet and are predicted to start supplanting 100 Gigabit Ethernet in data centers around 2020. Given the aforementioned time lag between ecosystem development and application in PON systems, we can expect commercially ready 50G TDM-PONs in the middle of the next decade. Refer again to Figure 1.

Most 50 Gb/s channels will be implemented with the 25 Gbaud optics developed for 100 Gigabit Ethernet, plus PAM4 modulation. More efficient 400 Gigabit Ethernet based on 100 Gb/s channels using 50 Gbaud optics and PAM4 modulation is being demanded by operators of “hyperscale” data centers. Some 50 Gbaud components are already commercially available. Once again, the data center trickle-down paradigm should hold.

Compared to 25G TDM-PON, 4-5 more dBs are required for 50G. This time, optical amplification cannot be avoided. SOA preamplifiers may not give the required improvement, in which case SOA post amplifiers would be needed. PAM4 has a 4.8 dB theoretical modulation penalty and in implementation is worse, maybe too high to be compensated by optical amplification\(^4\). The required digital signal processing might prove problematic for cost-effective ONUs. Therefore, NRZ modulation should be considered. 50 Gbaud transmitters could be shipping in high volumes by the middle of next decade. These might need to be integrated with SOA post amplifiers. The problem may be on the receiver side: the availability of low cost

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50 Gbaud APDs. The solution can be electro duobinary or MLSE detection with 25 Gbaud APDs, which would also increase dispersion tolerance.

**Possible paths to a 100G TDM-PON: coherent**

To fulfill a 29 dB loss budget, 100G TDM-PON will probably require a coherent receiver. For symmetrical 100G, a coherent burst mode receiver will be required; this is an active area of research\(^5\),\(^6\). There are at least three possible scenarios that could lead to a practical 100G coherent PON in the second half of the next decade:

- Sufficient cost erosion of traditional 100G coherent, 28 Gbaud PM-QPSK, occurs in time for the market need. This would be a return to the old long-haul-to-metro-to-PON paradigm.
- Data centers adopt coherent in the early/mid 2020s. High volumes drive low-cost coherent components. This would be a continuation of the data-center-to-PON paradigm.
- A new IM-coherent detection scheme attains PON cost targets more quickly than 28 Gbaud PM-QPSK. Perhaps what would be needed is a stripped-down coherent architecture optimized for PONs.

With digital signal processing, coherent PON could use the S, C or L wavelength bands, since chromatic dispersion can be fully compensated, easing wavelength co-existence with legacy PONs in the crowded O-band.

At any rate, the PON industry has at least 5 years before making technology decisions about 100G PON.

**Acronyms**

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<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>APD</td>
<td>Avalanche photodiode</td>
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<tr>
<td>BPN</td>
<td>Broadband PON</td>
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<tr>
<td>DAA</td>
<td>Distributed access architecture</td>
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<tr>
<td>dB</td>
<td>Decibel</td>
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<td>DML</td>
<td>Directly modulated laser</td>
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<td>DOCSIS</td>
<td>Data Over Cable Service Interface Specification</td>
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<tr>
<td>EML</td>
<td>Electro-absorption modulated laser</td>
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<tr>
<td>EPON</td>
<td>Ethernet PON</td>
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<tr>
<td>FSAN</td>
<td>Full Service Access Network Group</td>
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<tr>
<td>GPON</td>
<td>Gigabit PON</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>IM-coherent</td>
<td>Intensity modulation-coherent</td>
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<td>MLSE</td>
<td>Maximum Likelihood Sequence Estimation</td>
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<td>NRZ</td>
<td>Non-return-to-zero</td>
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OC-14/48/192  Optical carrier rates
OLT            Optical line terminal
ONU            Optical network unit
PAM            Pulse amplitude modulation
PM-QPSK        Polarization-multiplexed quadrature phase shift keying
PON            Passive optical networks
SerDes         Serializer/deserializer
SOA            Semiconductor optical amplifiers
STM            Synchronous transport module
TDM            Time-division multiplexing
TIA            Transimpedance amplifier
VR             Virtual reality
WDM            Wavelength-division multiplexing

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