Current and next-generation PONs: A technical overview of present and future PON technology

Elmar Trojer, Stefan Dahlfort, David Hood and Hans Mickelsson

The authors describe the evolution of GPON and associated trends in the industry. They briefly introduce and compare current PON technologies and describe options for reach-extended GPON and next-generation access systems.

Introduction to passive optical networks

Video components in the service bundle call for higher bandwidth, forcing most telecommunications operators to contemplate upgrading or completely renewing their copper-centric legacy access networks. Gigabit-capable passive optical networks (GPON) and Ethernet passive optical networks (EPON) are two standards that open the door to new opportunities both for vendors and operators.

Major vendors, including Ericsson, have added PON technology to their broadband access portfolios, and operators around the world have shown considerable interest in deploying this technology in combination with VDSL2 (fiber to the cabinet, FTTC) or as resale. The three major PON standards are BPON (broadband PON, currently only of historical interest), GPON, and EPON.

BPON and its successor GPON are ITU-T recommendations sponsored by FSAN, a vendor and operator committee. EPON is an IEEE option developed by the IEEE Ethernet in the First Mile (EFM) initiative. Given that operators are driving GPON standardization via FSAN, the GPON standard reflects operator needs more directly than does EPON.

Although all three systems work on the same principle, there are several differences between them (see Table 1).

IEEE Ethernet in the First Mile (EFM) initiative. Given that operators are driving GPON standardization via FSAN, the GPON standard reflects operator needs more directly than does EPON.

All three systems work on the same principle, there are several differences between them (see Table 1).

GPON evolution

After some minor initial deployments of BPON, the industry realized too late that a BPON-based optical distribution network (ODN) could not be incrementally upgraded to any next-generation technologies. In short, the logistics of upgrading an entire PON simultaneously were daunting, and the cost of installing a parallel upgrade PON was prohibitive. Out of this experience grew the requirement that it must be possible to make incremental next-generation upgrades on the same ODN.

There were, and still are, many candidates for next-generation PON systems. The ITU community thus drafted G.984.5, which reserved wavelengths for use by next-generation applications without constraining them. By contrast, the EPON community saw bandwidth limitations as the most serious problem and immediately began work on 10Gbps EPON (802.3av) as the successor to 1Gbps EPON.

The economics of real deployments also led ITU-T, encouraged by FSAN, to start working on a reach-extension standard for GPON, provisionally designated G.984.re. This specification allows optical amplifiers or signal regenerators to be used:

- to extend reach to 60km;
- to increase the split ratio; or
- to achieve a combination of both.

The next-generation architecture (NGA) defines two stages of evolution (Figure 1): NGA1 and NGA2. NGA1 is compatible with GPON deployments in accordance with G.984.5. Compatibility with a GPON reach extender is also expected, but has not yet been explored in detail. It is anticipated that NGA1 systems will be commercially available around 2010. Some NGA1 candidates are:

- XGPON1, which supports data rates of 10Gbps downstream and 2.5Gbps upstream;
- symmetric XGPON2, which supports 10Gbps downstream and upstream; and
- WDM option to overlay PONs and point-to-point connections on the same fiber infrastructure in G.984.5 enhancement bands.

Recognizing that G.984 definitions will not be suitable forever and new developments will obviate the need for backward compatibility, ITU-T has not constrained NGA2 by the GPON ODN. It is anticipated that NGA2 products will be available around 2015. NGA2 may use a new fiber network, introducing in particular the ability to use dense wavelength-division multiplexing (WDM) splitters instead of power splitters to separate users via different wavelengths on the same ODN.

Long-reach PON

Basic GPON systems support a maximum physical reach of 20km on a 32-way split or 10km on a 64-way split. Although this seems sufficient for most deployment cases, the industry seeks an extended link budget for two reasons:

- Longer reach: Reach-extended PONs supporting 100km would allow thousands of today’s central offices to be consolidated to a handful of huge metro nodes, thereby simplifying the network architecture and

### TERMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPON</td>
<td>Broadband PON</td>
</tr>
<tr>
<td>CDR</td>
<td>Clock detection and recovery</td>
</tr>
<tr>
<td>DSL</td>
<td>Digital subscriber line</td>
</tr>
<tr>
<td>EFM</td>
<td>Ethernet in the first mile</td>
</tr>
<tr>
<td>EPON</td>
<td>Ethernet PON</td>
</tr>
<tr>
<td>FEC</td>
<td>Forward-error correction</td>
</tr>
<tr>
<td>FSAN</td>
<td>Full-service access network</td>
</tr>
<tr>
<td>FTTC</td>
<td>Fiber to the cabinet</td>
</tr>
<tr>
<td>FTTH</td>
<td>Fiber to the home</td>
</tr>
<tr>
<td>GPON</td>
<td>Gigabit-capable PON</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical &amp; Electronics Engineers</td>
</tr>
<tr>
<td>ITU-T</td>
<td>International Telecommunication Union – Telecommunication Standardization Sector</td>
</tr>
<tr>
<td>NGA</td>
<td>Next-generation architecture</td>
</tr>
<tr>
<td>OA</td>
<td>Optical amplifier</td>
</tr>
<tr>
<td>OAM</td>
<td>Operation, maintenance and administration</td>
</tr>
<tr>
<td>ODN</td>
<td>Optical distribution network</td>
</tr>
<tr>
<td>OLT</td>
<td>Optical line termination</td>
</tr>
<tr>
<td>ONU</td>
<td>Optical network unit</td>
</tr>
<tr>
<td>ONU</td>
<td>Optical network unit</td>
</tr>
<tr>
<td>ONU</td>
<td>Optical network unit</td>
</tr>
<tr>
<td>ONU</td>
<td>Optical network unit</td>
</tr>
<tr>
<td>PON</td>
<td>Passive optical network</td>
</tr>
<tr>
<td>QD-SOA</td>
<td>Quantum-dot SOA</td>
</tr>
<tr>
<td>RE</td>
<td>Reach extender</td>
</tr>
<tr>
<td>RPT</td>
<td>Remote protocol terminator</td>
</tr>
<tr>
<td>SDH</td>
<td>Synchronous digital hierarchy</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor optical amplifier</td>
</tr>
<tr>
<td>TDF</td>
<td>Thulium-doped fiber amplifier</td>
</tr>
<tr>
<td>TDM</td>
<td>Time-division multiplexing</td>
</tr>
<tr>
<td>VDSL2</td>
<td>Very high-speed DSL 2</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength-division multiplexing</td>
</tr>
</tbody>
</table>
reducing operating expenses. A modest increase in budget would make it possible to reach remote customers.

- **Increased split ratio**: A split ratio of 64 or even 128 would reduce the cost per subscriber of a PON system. PON technology is being driven by the need for higher bandwidth, but low take rates also mean that the business case for high-rate services is a future promise rather than a current fact. As a consequence, operators want to serve a large number of basic users from each PON by sharing common equipment.

There are two basic ways of extending reach (Figure 2). A single-sided extender enhancing the optical transceiver function of the optical line termination (OLT) keeps the ODN passive and allows for a limited budget increase (Figure 2, top).

An active mid-span extender (reach extender, sometimes designated RE), as currently drafted in G.984.re, would allow the optical trunk line to be extended to achieve a total reach of 60km. This represents the maximum logical reach of the GPON protocol layer (Figure 2, bottom).

To succeed, a reach extender must comply with the following fundamental requirements:

1. It must be cost-effective – that is, there must be a business case that supports the deployment of reach extenders (cost benefits over keeping exchange buildings).
2. It must be transparent to existing GPON OLTs situated on the network side and optical network terminations (ONT) on the user side.
3. It must be available for early GPON deployment.

Figure 3 compares different approaches to enhancing the performance of reach extenders.

**Optically amplified PONs**

Optical amplifiers (OA) can be used in GPON either to boost transmit power and receiver sensitivity on the OLT side or to work as an in-line amplifier in mid-span reach extenders.

A typical GPON RE based on amplification comprises

- wavelength filters to separate upstream and downstream signals;
amplifier for each direction; and
- optical bandpass filters in the upstream and possibly downstream directions for noise limitation.

Fiber and optical amplifiers can be used to extend the reach of a GPON system with a 64-way split to 60km. Thulium-doped fiber amplifiers (TDFA), quantum-dot semiconductor optical amplifiers (QD-SOA) and Raman amplifiers are employed in the downstream band (S-band), and praseodymium-doped fiber amplifiers (PDFA) and QD-SOAs are employed in the upstream band (O-band).

Table 2 gives a high-level summary of the pros and cons of different amplifier technologies in an ODN. Note: he numbers in parenthesis indicate the relative performance of the different amplifier characteristics.

As can be seen, semiconductor optical amplifiers (SOA) are the most promising breed of amplifiers. Nevertheless, SOA-based reach extenders exhibit high noise figures (especially in the O-band) and are comparatively expensive. On the other hand, REs based on optical amplification are technically achievable but practically questionable due to transparency and cost:

- **Transparency**: OA as for GPON bands are not transparent. Even when equipped with filters, noise results in a reduced-extinction ratio, which is incompatible with standard OLT receivers. To achieve carrier-class performance, new OLT blades would have to be designed, which violates rules 2 and 3 for REs.
- **Cost**: Optical components (SOAs and fiber amplifiers) are prohibitively expensive (rule 1).

**Regenerated PONs**

In a regenerated PON, the signal is refreshed by means of optical-electrical-optical conversion. Figure 4 illustrates a typical 3R RE (3R: reamplify, re-shape and re-time the signal). The 3R RE contains OLT and ONT transceivers as well as clock detection and recovery (CDR) units for upstream and downstream directions (a burst CDR is needed for the upstream).

For management and alarms, the RE may contain an optical network unit (ONU) that terminates physical layer OAM and the OMCI (ONT management control interface) management channel. The embedded ONU is part of the management model currently under discussion in G.984.re.

REs based on signal regeneration also exhibit some problems:
- **Burst recognition from ONT**: For the RE to decode upstream bursts correctly, basic GPON framing parameters, such as the preamble and inter-burst gap, must be extended, which results in a loss of protocol efficiency and transparency (rule 2).
- **Software incompatibilities**: Delay and optical layer measurements lose their standardized meaning. Likewise, troubleshooting becomes more complicated, because new alarm correlations and suppression must be added, which increases complexity and cost.
- **Issues with standard OLT**: A 3R RE renders some OLT burst receiver functionality and OLT dynamic range capabilities worthless.

This further motivates the need for special OLT blades (rule 2).

**Remote protocol termination**

Purpose-built for a TDM-shared optical tree, the G.984 protocol was never intended to compete with robust protocols such as asynchronous digital hierarchy (SDH) or 802.3 Ethernet on point-to-point links.

Reach extension is nothing more than adding a long point-to-point trunk line to the point-to-multipoint GPON ODN. On the trunk line, however, the point-to-multipoint specialization of the GPON protocol is a disadvantage in terms of receiver...
synchronization, dynamic range, burst mode power management, noise margins and jitter budget. Moreover, the benefits of protocols designed for point-to-point transmission links are not available. Hence, the remote protocol terminator (RPT), which circumvents these problems.

In terms of delay, budget, split ratio, maintenance, existing silicon, existing optical components, and software, an RPT looks exactly like a GPON OLT to the shared part of the ODN (the TDM tree). But instead of the PON protocol, the RPT uses the right tool for each exchange. For best results, 10Gbps Ethernet uplinks are recommended, although one may use SDH depending on market interest. Standard Ethernet protection schemes, such as link aggregation group (802.3ad) and rapid spanning tree protocol (802.1w), exist for a redundant system.

The RTP has been designed to host next-generation access technology options, such as higher speed TDM-based PONs, WDM-based PONs, or both.

Estimates show that the cost, size and power consumption of a protected remote site RPT are the same as for a regenerator but considerably less than for an optical amplifier (rule 1). In contrast to other RE approaches, an RPT is based on existing technology, standards, and components (rule 2) and can be delivered within the normal product development time frame (rule 3). Table 3 compares G.984.1e REs and the RPT.
Next-generation access

Now that GPON has been standardized and is in production, the optical access community has begun discussing candidate technologies for next-generation access. The high-level requirements for an NGA system are already clear, as follows:

1. Fiber-lean scenario – that is, coexistence with working GPON on the same ODN. NGA must support upgradeability, one subscriber at a time.
2. Major improvement in performance over GPON in terms of rate and reach or split.
3. Volume cost comparable to GPON. Service overlay a la G.984.5

G.984.5 defines wavelength ranges reserved for additional service signals overlaid via WDM. In particular, it includes

- wavelength ranges to be reserved for future use (Figure 5) – G.984.5 specifies three optional enhancement bands with option 1 in the E band (water-peak band), option 2 in the C- and L-bands, and the RF band, as option 3, for future services provided video overlay is not deployed;
- wavelength-blocking characteristics for filters that protect the GPON downstream signal in the ONT/ONU from interference from the new bands; and
- GPON upstream wavelength-reduction options, to free spectrum in the O-band for future services. In all likelihood the distributed feedback (DFB) laser option will be most widely deployed.

XGPON and overlaid PONs

There are basically two ways of increasing the capacity of a TDM-based PON system for NGA in compliance with the main requirements.

Figure 6 shows that one can speed up a regular 2.5Gbps GPON system to 10Gbps (XGPON) and overlay it on a separate G.984.5 wavelength. One might also overlay four colored 2.5Gbps GPON systems via WDM multiplexers on four different wavelengths on the same ODN to obtain 10Gbps overall system capacity.

The complexity and cost of an XGPON system is in the high-power, high-speed optical transceivers, which use electro-absorption modulated lasers. The ODN itself remains unchanged. The cost of an overlaid PON is dominated by the multiplexation of OLT equipment and the interim upgrade of the
ODN with wavelength-selective splitters (hybrid splitters, which comprise low-ratio power splitters and four-channel WDM multiplexers).

Ericsson has put considerable effort into pursuing the XGPON track and is currently demonstrating an experimental high-speed GPON system that, following the principles of coexistence and low-cost design, supports 10Gbps downstream and 2.5Gbps upstream. In light of an RPT, the key parameters for a next-generation system are high port density, small footprint, and reduced power consumption.

**Conclusion**

Current GPON technology is a powerful option for deep-fiber broadband access. Serious efforts to standardize and develop this technology have steadily extended the feature set of GPON to make the technology more flexible in terms of deployment and services and to make the fiber infrastructure “future-proof.”

The long-reach option, as currently specified in FSAN, will make it possible to use active reach extenders to increase the span of the system to 60km. This approach can be employed to reach remote customers or to host more users on a PON.

In terms of coexistence, GPON is fully prepared for the future. Next-generation systems – for instance, XGPON, overlaid PON, or some other technology, will work on the GPON fiber infrastructure, allowing operators to capitalize on their investments for decades to come.

Ericsson’s upgrade strategy is very clear in terms of long-reach and next-generation optical access using remote protocol termination and XGPON.

**REFERENCES**

1. Bernstein Research: Fiber: Revolutionizing the Bell’s Telecom Networks. May 2004
4. G.983.1-5, A broadband optical access system with increased service capability by wavelength allocation. ITU-T, 03/2001
7. Full-service Access Network (FSAN), www.fsanweb.org