An Introduction to PON Technologies

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ABSTRACT

Passive optical networks are the most important class of fiber access systems in the world today. This article first reviews the reasons why the PON as a general architecture is so important. We then outline in some depth the technologies used to implement this architecture, including the G-PON and E-PON systems being deployed today, and the advanced PON systems that provide the evolution path to ever higher bandwidths.

INTRODUCTION: THE MOTIVATION FOR PON

One of the most critical decisions for any business involves the purchase of capital equipment. Of the many factors that influence this decision, equipment cost and the resulting revenue potential are two of the most important. Service providers face this decision when upgrading existing access networks or expanding into new areas. They want to minimize the cost of deploying access equipment while maximizing revenue from the service offerings. Of these two parameters, the cost of deployment is easier to determine than revenue potential because future revenue involves considerable speculation. As a result, the raw bandwidth capabilities of an access technology are often used as a proxy for revenue potential. Thus, the most important decision a service provider makes when purchasing network equipment is how to strike a balance between minimizing the equipment cost and maximizing the bandwidth.

The passive optical network (PON) is just one of several access technologies used by service providers, but it enjoys a dominant position in the access market. Before discussing the specific details of the PON, it is worthwhile to survey the alternate access technologies in order to understand the reasons for the PON's success.

Access networks fall into three categories: wireless, copper, and fiber. Wireless has the lowest deployment cost because it has the lowest outside plant costs. WiFi (802.11) and WiMAX (802.16) are the standards for wireless access and broadband access. WiMAX is a recently adopted IEEE standard that was designed for fixed and mobile access networks. It has a useful range of about 5 km at a data rate of 70 Mb/s. WiFi is more mature than WiMAX, but it has a range of only 100 m and a bit rate of 10–50 Mb/s. In spite of this limitation, WiFi is more widely used for access today than WiMAX due to its maturity.

Although both WiFi and WiMAX are relatively low cost to deploy, they lack sufficient bandwidth to support video applications. These wireless technologies use a point-to-multipoint architecture. This means that bandwidth is shared by multiple users — in some cases hundreds of users. Consequently, WiFi and WiMAX are useful for Web surfing applications, but impractical for higher-bandwidth and higher-revenue applications such as IPTV.

Another access technology option available to service providers is copper — more specifically, digital subscriber line (DSL) over copper. Unlike wireless, DSL uses a point-to-point architecture. So instead of sharing 50 Mb/s over all subscribers, DSL can provide 50 Mb/s to each subscriber. Unfortunately, DSL shares a shortcoming with wireless: it is a noise-limited access technology. In other words, the effective bandwidth DSL provides to a subscriber depends on the level of noise, which in turn depends on the length of the copper loop. DSL is capable of 50 Mb/s for loop lengths less than 300 ft, but can only provide 10 Mb/s at 10,000 ft. If operators want to offer a compelling video service with 30 Mb/s, they need to shorten loop lengths to roughly 3000 ft or less. This is a viable approach, but the cost is only slightly lower than an all-fiber approach.

The final option to consider for access technology is fiber. An access network can be architected using either dedicated or shared fibers. A dedicated fiber plant, often referred to as a point-to-point network, provides a dedicated fiber strand between each subscriber and the central office (CO).

In a shared fiber architecture, a single fiber from the CO serves several dozen subscribers. This fiber is brought to a neighborhood where the signals are broken out onto separate fibers that run to the individual subscribers.

Point-to-point fiber networks have a low market penetration mainly due to the additional cost

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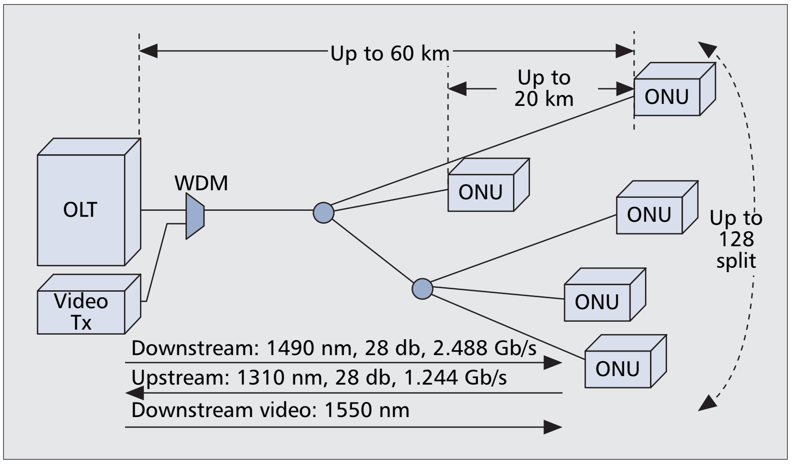


Figure 1. *G-PON physical network architecture.*

it adds over a shared fiber infrastructure. Depending on the average loop length, the construction costs of outside plant based on dedicated fiber exceed those of outside plant based on shared fiber by anywhere from 20 percent to 100 percent.

In shared fiber architectures, there are two ways the signals are broken out. One method is called active Ethernet (AE), and the other is the PON. With AE the individual signals are split out using electronic equipment near the subscriber. In the PON the signals are replicated passively by the splitter.

A shared network based on a PON has several advantages over one based on AE. The outside plant of a PON incurs lower capital expenditures as it has no electronic components in the field. The PON also lowers the operational expenditures, since there is no need for the operators to provide and monitor electrical power in the field or maintain backup batteries. A PON has a higher reliability than AE because in the PON outside plant there are no electronic components, which are prone to failure. Lastly, perhaps one of the most crucial features of a PON-based access network is its signal rate and format transparency. Upgrading to higher bit rates is simpler for a PON than for AE. Both require upgraded electronics in the CO and customer premises, but, unlike AE, there is nothing that needs upgrading in the outside plant for a PON, as the passive splitters are agnostic to PON speed. For all of the reasons cited above, the PON is by far the most widely deployed access technology. The rate and signal format transparency became a sort of insurance policy that eased carriers into deploying PON outside plants with the understanding that an access network could flexibly be upgraded as new technologies mature or new standards evolve.

Not surprisingly, this article is dedicated to various flavors of PONs that all use the same or very similar outside plants, but differ significantly in signaling rates, data formats, or protocols they employ. These PON technologies include Gigabit PONs, Ethernet PONs, and wavelength-division multiplexing (WDM) PONs.

GIGABIT PASSIVE OPTICAL NETWORKS

STANDARDIZATION HISTORY

The gigabit-capable PON (G-PON) is specified by International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) G.984 series [1-4]. G-PON definition began in the Full Service Access Network (FSAN) consortium in 2001. In January 2003 the first two standards were approved by the ITU-T, covering the requirements and basic architecture (G.984.1), and the physical-medium-dependent (PMD) layer (G.984.2). In February 2004 G.984.3 specifying the G-PON transmission convergence (TC) layer was ratified, followed by G.984.4, which standardizes the G-PON management requirements. Since then, a few amendments have reached consent by the ITU-T on most of the documents in the series.

PMD LAYER

The G-PON network architecture supports a two-wavelength WDM scheme for downstream and upstream digital services (Fig. 1). Additionally, another downstream wavelength is allocated for distribution of analog video service. The network supports up to 60 km reach, with 20 km differential reach between optical network units (ONUs). The split ratio supported by the standard is up to 128. Practical deployments typically would have lower reach and split ratio, limited by the optical budget.

ITU-T G.984.2 specifies the PMD layer for G-PON, covering the range of G-PON upstream and downstream bit rates, and the optical parameters for the various rate combinations.

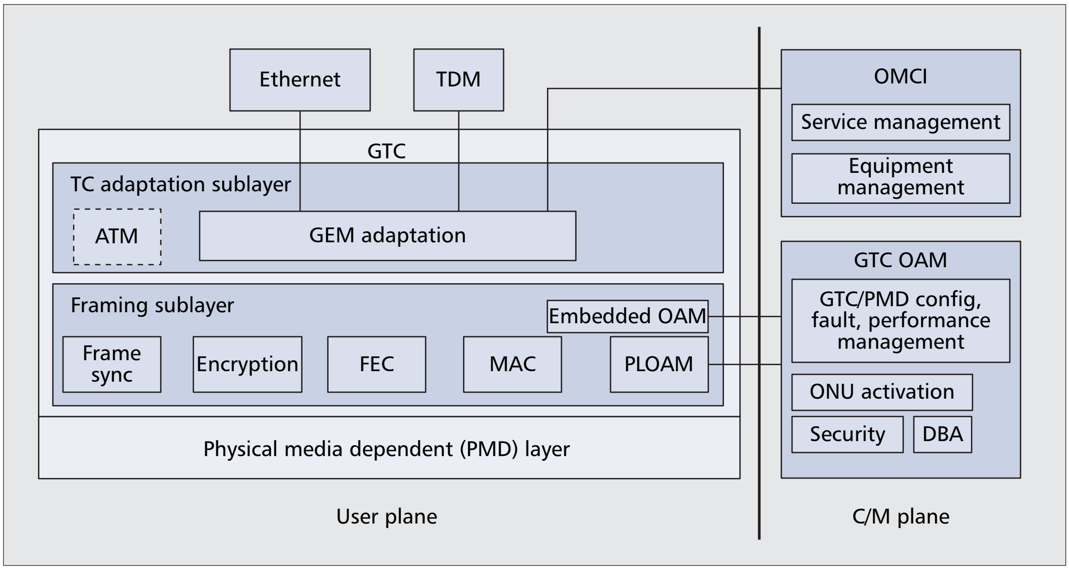
As network operators requirements evolved, the preferred G-PON bit rate was selected to be 2.488 Gb/s downstream, 1.244 Gb/s upstream. This focus has then allowed the definition of best practice optical parameters for G-PON, which was documented as an amendment to G.984.2. The parameters, known as Class B+, apply to a network with or without a video overlay and to ONUs based on either APD or PIN technology.

GTC LAYER

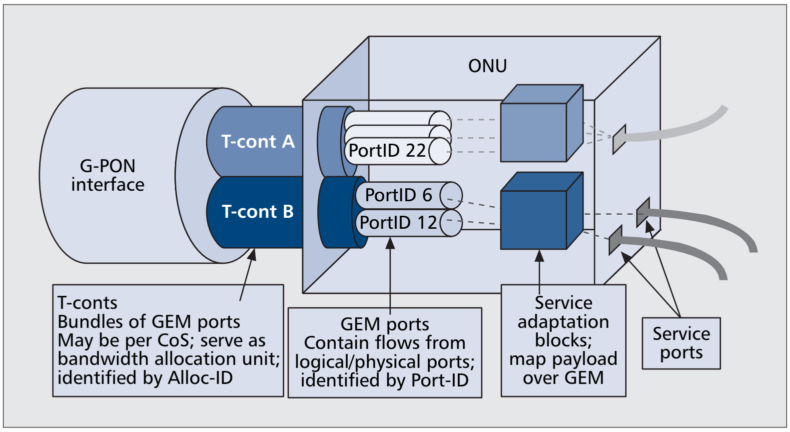
The G-PON TC (GTC) layer specified by [3] performs the adaptation of user data onto the PMD layer. Additionally, the GTC layer provides basic management of the G-PON network.

The GTC layer defines two adaptation methods for data transport: asynchronous transfer mode (ATM) and G-PON-encapsulation-method (GEM). However, as GEM has become the preferred method, ATM is not discussed hereafter. GTC with GEM allows low overhead adaptation of various protocols, including Ethernet and time-division multiplexing (TDM). GTC also provides the medium access control (MAC) function, coordinating the interleaving of upstream transmissions from multiple ONUs.

The control functions of GTC consist of a protocol and procedures for registering ONUs to the G-PON network, and monitoring their health



■ **Figure 2.** *G-PON functional relationships and layering.*



■ **Figure 3.** *The hierarchy of G-PON multiplexing: ports, T-Conts, and PONs.*

and performance. GTC also allows configuration of transport features such as forward error correction (FEC), encryption, and bandwidth allocation. Figure 2 illustrates GTC layering, and the main functions of the user and control planes.

The GTC is divided into two sublayers. The lower framing sublayer defines the GTC frame structure, which is asymmetrical, carrying different overhead information downstream vs. upstream. The GTC uses a 125 μs downstream frame, and also transports an 8 kHz signal that provides a reference clock to the ONUs. The upstream frame comprises a sequence of transmissions from ONUs as dictated by the optical line terminal (OLT). GTC framing in both directions is rate agnostic; that is, different G-PON rates maintain the same frame structure and vary only in the amount of payload.

The downstream GTC comprises the physical control block (PCBd), a header containing all overhead fields, followed by the payload part. The PCBd includes framing related fields, and the physical layer operations, administration, and maintenance (OAM) (PLOAM) field. The PLOAM carries a message-based protocol for PMD and GTC layer management. Finally, the PCBd includes the bandwidth map field specifying the ONUs' upstream transmission allocation.

On the GTC upstream, each ONU transmission is headed by a physical layer overhead field (PLOu), including a preamble and delimiter, which are configurable by the OLT. To assist with dynamic bandwidth allocation (DBA), the PLOu may include the dynamic bandwidth report field (DBRu), which carries traffic queuing reports from ONUs. The PLOu may also include a PLOAM field of identical format to the downstream PLOAM. The PLOAM and DBRu are optional and present in a frame only upon OLT request.

The higher sublayer of GTC is the TC adaptation sublayer based on GEM. GEM defines a protocol-independent connection-oriented encapsulation for variable-size packets. GEM's virtual connection unit is called a GEM port, and may contain a flow to/from a physical or logical port of an ONU. GEM frames include a 5-byte header indicating the port ID and length of the frame. GEM frames may be fragmented; hence, a client packet may span multiple GEM frames. G.984.3 includes appendices specifying transport of Ethernet and native TDM over GEM.

Figure 3 illustrates GEM ports' flow in the context of the G-PON multiplexing hierarchy. As shown, GEM ports are bundled onto transmission containers (T-conts). A T-cont is the unit of upstream bandwidth allocation by the OLT. The T-cont arrangement is configurable by the OLT; however, popular schemes are a single T-cont per ONU, or multiple T-conts, one per service class, per ONU.

The OLT bandwidth allocation method for ONU upstream transmission may be static or dynamic (DBA). Two methods of DBA are defined for G-PON: status-reporting DBA, which is based on ONU reports via the DBRu

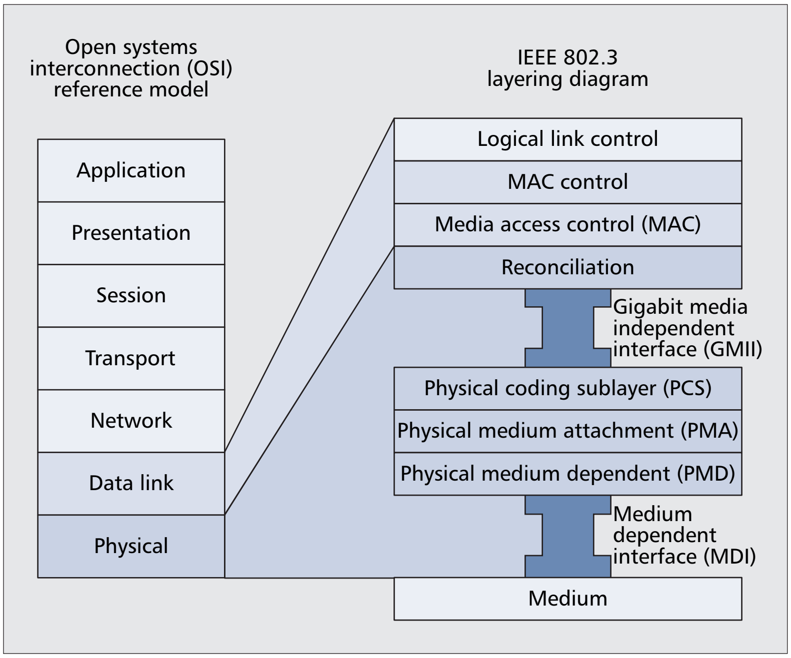


Figure 4. *Relationship of IEEE 802.3 layering model to OSI reference model.*

field, and non-status-reporting DBA, which is based on OLT monitoring per T-cont utilization. Refer to [5] for a more detailed description of SR-DBA.

The GTC layer control plane is mainly operated via the PLOAM message protocol and some overhead fields referred to as *embedded OAM*. It includes the following management functions:

- PMD layer management — Configuration of upstream overhead; monitoring health of physical layer, and generation of alarms or statistics accordingly.
- GTC layer management — Configuring GTC framing options, such as usage of upstream/downstream FEC, requesting PLOAM, DBRu, and so on.
- ONU activation — The GTC layer defines the process to activate an ONU on the G-PON network, including a ranging procedure to measure the ONU distance and set its equalization delay. The optical power level of the ONU may also be tuned.
- Encryption management — GTC mandates Advanced Encryption Standard (AES) as its downstream encryption mechanism, with a per-ONU encryption key. Encryption may be selectively applied on a per GEM port ID basis. A procedure is defined for key exchange.

G-PON MANAGEMENT

Network operators require full management of G-PON systems' equipment and services, while supporting interoperability between ONUs and OLTs of different vendors. G.984.4 specifies the ONT management and control interface (OMCI) to address those requirements.

OMCI comprises a full ONU management information base (MIB), and the ONT management control channel protocol (OMCC) that conveys MIB information between the OLT and ONUs. The MIB comprises a set of managed entities, each containing a set of attributes. Creation of managed entities and their attributes is designated to either the OLT or ONU.

Since G-PON ONUs may support a broad variety of interfaces and services, OMCI modeling is very rich in content. However, each MIB instance, representing a specific ONU, contains a small subset of objects. OMCI models physical aspects of the ONUs, such as their equipment configuration, power, and various port types, such as plain old telephone service (POTS), Ethernet, xDSL, T1/E1, radio frequency (RF) video, and MoCA. At the service layer, OMCI covers high-speed Internet access using various flow classifications and quality of service (QoS) schemes, TDM-voice, voice over IP (VoIP), circuit emulation service (CES), IPTV, and more. For each of those objects OMCI supports configuration, fault, and performance management. Additionally, OMCI standardizes the software download for ONUs and the housekeeping of the MIB itself.

FUTURE G-PON EXTENSIONS

A few G-PON enhancements are currently in the works. They include the following:

- Definition of wavelength blocking filters. The filters would be supported at G-PON ONUs to ensure that next-generation ONUs using additional wavelengths could in the future be installed on currently deployed G-PON optical data networks (ODNs) side by side with G-PON ONUs.
- Extension of a G-PON's optical budget to allow deployment of longer reach and higher split ratio. This may require an active extender box to be deployed at the ODN.
- Inclusion of higher data rates. The downstream rate would likely be 10 Gb/s, but the upstream rate is still an open question of 2.5, 5, or 10 Gb/s.

ETHERNET PASSIVE OPTICAL NETWORKS

EPON HISTORY

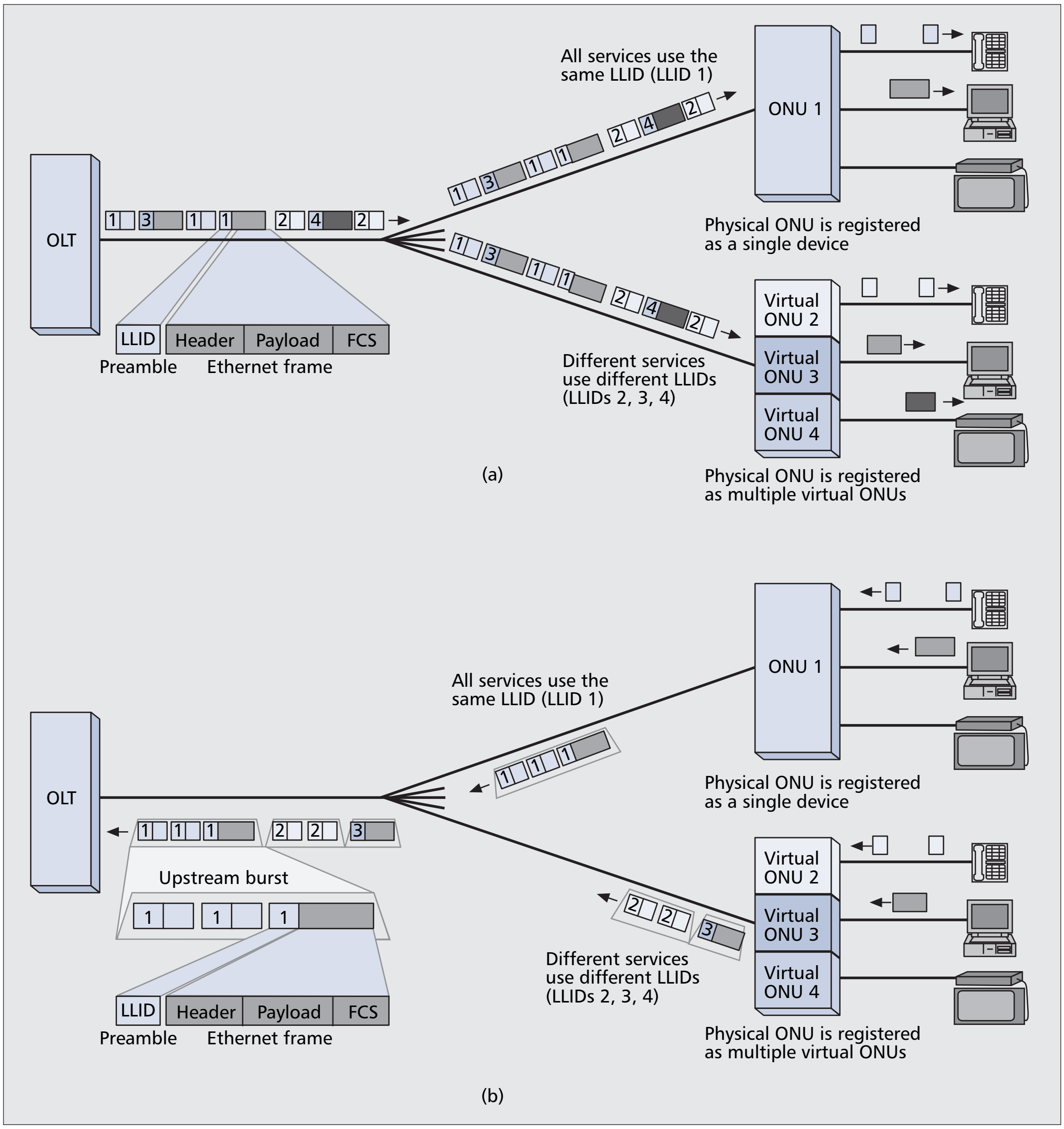
In November 2000 IEEE 802.3 announced a call for interest for a new study group called Ethernet in the First Mile (EFM). The group was to extend Ethernet into the subscriber access area.

Ethernet over point-to-multipoint (P2MP) fiber (also known as EPON) became one of the focus areas of this group, along with Ethernet over copper, Ethernet over point-to-point (P2P) fiber, and OAM tracks. In September 2001 the IEEE Standards Board approved the EFM Project Authorization Request, resulting in the formation of the P802.3ah task force.

The EFM task force completed its charter in June 2004, culminating in ratification of IEEE 802.3ah [6].

SCOPE OF WORK

IEEE 802.3 focuses on two lower layers of the open systems interconnection (OSI) reference model [OSI94]: the physical and data link layers. Each of these layers is further divided into sublayers and interfaces. Figure 4 shows the sublay-



■ **Figure 5.** *EPON a) downstream operation; b) upstream operation.*

EPON's Ethernet roots are unmistakable. EPON traffic uses the same Ethernet packet format, with standard IPG, as found in any enterprise switch. For that matter, EPON uses the same MAC found in any IEEE 802.3-compliant device.

ers and interfaces defined for Ethernet devices operating at 1 Gb/s data rates.

EPON TECHNOLOGY

EPON technology provides bidirectional 1 Gb/s links using 1490 nm wavelength for downstream and 1310 nm for upstream, with 1550 nm reserved for future extensions or additional services, such as analog video broadcast.

EPON's rapid adoption was driven by the early decision to define the physical layer specification using relatively minor modifications to inexpensive high-volume 1 Gb/s optical components. This has greatly reduced optics cost to levels comparable to those of continuous mode optics.

Using the same philosophy of "define the specification for rapid high-volume deployment," the EPON upstream burst lock timing was relaxed to use available continuous mode mixed signal components. The downside is somewhat lower upstream utilization, but since other access technologies are far more asymmetric, this slight difference was deemed minor.

While in the IEEE 802.3ah standard EPON link budget was conservatively specified as 24 dB with minimum 1:16 split ratio, in practice the transceiver technology has matured enough so that components providing 29 dB power budget became commercially available, resulting in most EPON-based networks being deployed with a 1:32 split ratio, with some as high as 1:64.

EPON's Ethernet roots are unmistakable. EPON traffic uses the same Ethernet packet format, with standard IPG, as found in any enterprise switch. For that matter, EPON uses the same MAC found in any IEEE 802.3-compliant device. The new P2MP connectivity is supported by a protocol called Multipoint Control Protocol (MPCP), which uses standard Ethernet packets generated in the MAC control sublayer.

EPON does not use encapsulating framing in either the upstream or downstream direction; instead, the content of the Ethernet preamble is modified. An upstream burst is simply a sequence of Ethernet packets with regular IPG between them, preceded by a longer sequence of

Expecting large-scale deployments of G-PON systems to start soon, network operators and system vendors are seeking NG-PON solutions that can coexist with GPON on the same fiber plant and enable gradual network capacity upgrades.

IDLE codes used for receiver synchronization. Any management or control information is delivered in normal Ethernet frames.

An ONU in customer premises equipment (CPE) is enumerated by the OLT in the CO equipment using an MPCP handshake. The process is:

- Using the discovery GATE message, the OLT sends a request to all unregistered ONUs to transmit.
- An unregistered ONU answers by using a REGISTER REQ registration request message.
- When received and approved, the OLT registers the ONU using the REGISTER message.
- The handshake ends with the ONU acknowledgment REGISTER_ACK.

During steady state operation, the OLT controls the ONU's transmission window with GATE messages. The ONU reports its queue status using REPORT messages. The OLT then calculates the ONU transmission window length using DBA.

All time-driven events are synchronized to the PON clock, a 16 ns resolution counter that is carried in all MPCP messages. The ONU uses the received timestamp to lock to the OLT time base. The OLT uses returned timestamps to measure ONU round-trip delay and schedule collision-free upstream transmissions.

EPON's packet preamble contains additional fields not found in packets sent over P2P Ethernet links. In downstream transmission the logical link ID (LLID) field defines the destination ONU. An ONU filters the received frames based on the LLID in the frame's preamble and its own unique LLID value assigned by the OLT (Fig. 5a). A special value is reserved for broadcast messages sent to all ONUs. In upstream transmissions the LLID field marks the source ONU (Fig. 5b). A cyclic redundancy check (CRC) field validates preamble integrity. Most ONU equipment registers as a single ONU and uses a single LLID for data transport. However, some equipment registers as multiple virtual ONUs, thereby establishing multiple LLIDs. This allows EPON to access the same traffic granularity on the PON as G-PON.

When a physical ONU registers as multiple virtual ONUs, the OLT treats each virtual ONU as a separate ONU. Correspondingly, the OLT grants each virtual ONU separately, including repeated allocation of the optical overhead. The OLT also maintains a separate management channel to each virtual ONU, and has to identify the SLA allocated to each virtual ONU.

EPON uses a frame-based FEC mechanism based on the RS(255,239) algorithm. Each frame is encoded separately, and all per-frame parity bytes are added at the end of the frame. This approach allows ONUs without FEC capabilities to receive FEC-encoded frames, ignoring the appended parity data. FEC can be selectively activated per ONU.

Although not defined in the IEEE 802.3ah specification, all EPON implementations incorporate encryption. Encryption is AES-based with the exception of a special algorithm defined by the major carrier in China for its network.

EPON MANAGEMENT LAYER

OAM functionality is another important EPON breakthrough. Ethernet now includes link layer management that enables OLTs to remotely manage attached ONUs.

OAM is established after the discovery process and is maintained by periodic message transmission. Information about remote failures is conveyed using flags in OAM messages to indicate failure status. The remote ONU can be instructed to return incoming packets as part of the remote loopback functionality.

Link monitoring, where any Ethernet variable of the remote port can be retrieved by the OLT, is arguably the most useful EPON OAM function.

OAM link information can be extended beyond the OLT by placing a Simple Network Management Protocol (SNMP) agent at the OLT. A soon to be finalized RFC, "Managed Objects of EPON," details the EPON MIBs [7].

An EPON CPE device contains much more than a MAC. OAM includes vendor extension mechanisms to provide a convenient and lightweight method to manage the additional functionality. This can lead to differing OAM variants as carriers customize their products.

FUTURE EPON EXTENSIONS

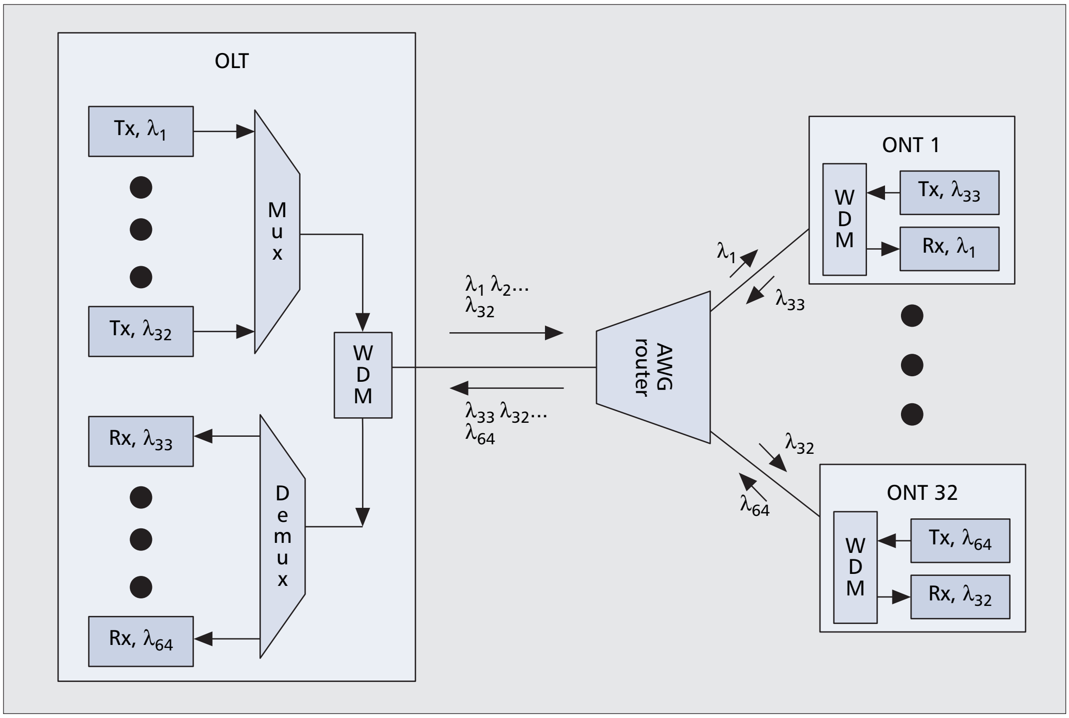
A significant EPON enhancement to run at higher speed has begun. The IEEE has formed the P802.3av task force to consider the definition of an EPON PHY that operates at 10 Gb/s downstream and 1 or 10 Gb/s upstream. This enhancement would provide a significant capacity increase for TDM PON systems.

NEXT-GENERATION PON SOLUTIONS

Historically, data rates associated with broadband consumer service offerings have increased at a rate of approximately 1.3 times/year. This growth has been driven by services such as convergent subscription television and the Internet, high-definition television, digital photography and video, new models for content production, distribution, and marketing, possible re-emergence of thin client computing, and so on. Projecting this trend into the future, in the long term we will face bandwidth demands beyond current G-PON capabilities, requiring R&D in this field already.

Different groups around the world have recently started to address this topic. Both FSAN and IEEE are now discussing ways how to extend their standards to 10 Gb/s line rates. Several research projects around next-generation PON (NG-PON) are investigating the topic on a wider scope, for example, the European PIEMAN and MUSE II projects in which different hybrid network solutions are evaluated that combine the classical TDM/time-division multiple access (TDMA) PON with WDM channel allocations as well as with optical amplification and transparent long-haul feeder transport.

Expecting large-scale deployments of G-



■ **Figure 6.** *A typical logically point-to-point WDM-PON architecture.*

A major drawback of WDM-PON as compared to TDM-PON such as EPON or GPON, is the requirement to provide multiple optical ports at the central office. To gain acceptance it is therefore required to use highly integrated multiple channel transmitter and receiver arrays.

PON systems to start soon, network operators and system vendors are seeking NG-PON solutions that can coexist with G-PON on the same fiber plant and enable gradual network capacity upgrades. At the same time, it is highly required to keep the fiber plant as transparent as possible while moving to NG-PON in order not to block further evolution paths. The time consuming and costly deployment of optical fibers, especially in the distribution plant and drop sections, must remain in place for decades without needing modifications or replacements.

WDM PON

WDM PONs have been actively researched as a potential technology for NG-PON. This PON uses multiple wavelengths in a single fiber to multiply the capacity without increasing the data rate. Different realizations have been proposed, of which a majority focus on the network architecture in which a passive wavelength router is used to replace the passive splitter in the PON fiber plant. As a result of this, each OLT-ONU pair has a dedicated and permanent wavelength assignment, and requires two transmitter/receiver pairs to form a point-to-point link (Fig. 6).

A passive wavelength router located at the remote node is realized by arrayed waveguide grating (AWG) or a set of thin film filters (TFFs). An AWG can operate over multiple free spectral ranges, permitting use of the same device for both downstream and upstream transmission. To allow for outside environments, an AWG needs an athermal design. AWGs have an optical loss of around 5 dB, which is about 12 dB less than that of a typical 1 × 32 power splitter. Taking into account the second AWG in the CO, a WDM-PON based on AWG architecture would reduce the link budget from 28 dB (class B+) to 21 dB, potentially allowing low-cost WDM sources to be used.

Upgrading an existing PON to the above P2P WDM-PON requires replacing the existing power splitter with an AWG router. However, this upgrade is not particularly desirable, as it requires work on the outside plant and disrupts existing customers. A centralized split PON (star topology) can relatively easily be upgraded to such a kind of WDM-PON. For distributed split PONs (tree and branch), it is impractical to take this upgrade path.

Another disadvantage of this approach relates to the loss of transparency of the outside plant. An alternative architecture that avoids this issue reuses the existing PON and keeps the power splitters in place. Wavelength selection at the ONU is performed using an additional bandpass filter (1 dB loss), and at the OLT by an AWG or a set of TFFs. A class B+ link budget is thus increased from 28 to 34 dB. This is compensated for by the fact that the line rate can now be reduced by a factor of four while still offering eight times the bandwidth per user of the original G-PON.

In the first scenario above (with the wavelength router at a remote node) the gained 7 dB link budget might as well be spent for an additional 1:4 power splitter after the router, thus offering, say, one (WDM adapted) G-PON per WDM channel instead of providing simple P2P connections. With the number of users per G-PON now being reduced to four, the bandwidth per user is again increased by a factor of eight, but now for 128 users.

Low-Cost WDM Sources

Unlike in dense WDM (DWDM) transport systems used in long-haul and metro networks, it is too expensive and impractical to implement

As the deployment of PONs grows into the many millions of homes served, it can be seen that a new era of access networks is upon us. The 100 year-long history of the copper network is finally coming to an end, and the age of PON has begun.

WDM PONs using DWDM lasers that emit unique or tunable wavelengths, particularly at the ONUs. Past and current research has been focused on finding low-cost solutions to provide so-called colorless ONUs so that a single type of ONU can be used everywhere in the WDM PON. A single type of ONU eliminates the issues related to inventory, maintenance, and installation associated with individual DWDM transmitters.

One early suggestion for realizing low-cost WDM sources is spectral slicing. With a broad optical spectrum source such as an LED, the WDM router or filter will automatically generate the "correct" wavelength channel from the input spectrum. Unfortunately, very high slicing losses of up to 18 dB make this approach less attractive than it might appear at first sight.

More recently, a WDM PON system based on wavelength-locked Fabry-Perot (FP) lasers, applying injection of spectrally sliced amplified spontaneous emission (ASE), was proposed and commercialized. The system consists of modified FP lasers as transmitters for both OLT and ONU. ASE generated from an Erbium doped fiber amplifier (EDFA) is sent from the CO through the transmission fiber. After passing through the AWG, it is spectrally sliced into multiple narrow bands, each of which is injected into the identical FP lasers at different ONUs, forcing them to operate on a single wavelength mode, different for each ONU, instead of emitting multiple modes. The most recent version of the product supports 16 WDM channels at 200 GHz spacing, each operating at 1.25 Gb/s and supporting about 21 dB ODN link budget.

In another approach WDM lasers located at the OLT send their unmodulated emission to the ONUs for modulation and then reflect this modulated light back to the OLT. A reflective semiconductor optical amplifier (RSOA) is used at the ONU to perform the modulation, amplification, and reflection. However, recent studies have shown that such schemes, even with optimized design, suffer from various reflection and backscattering issues, thus limiting the supported link budget to 16 dB, regardless of data rate.

A major drawback of WDM PON compared to TDM PON such as EPON or G-PON is the requirement to provide multiple optical ports at the CO. To gain acceptance, it is therefore necessary to use highly integrated multiple channel transmitter and receiver arrays. Optimized array designs also offer the potential to reduce electrical power consumption and heat dissipation.

IMPROVING THE OPTICAL POWER BUDGET

There is interest in exploring cost saving through service node consolidation by using a high splitting long-reach optically amplified PON. One early prototype version of such a system was called SuperPON, targeting 100 km and 2048 ONUs, and was developed by the European PLANET project in the mid-1990s. The present PIEMAN and MUSE II projects are heading toward similar figures, but additionally include the WDM dimension.

More near-term targets relate to extending the G-PON physical layer to its logical reach of 60 km and 128 ONUs. The goal is to maintain the G-PON current wavelength plan of 1480–1500 nm downstream and 1260–1360 nm upstream bands and to use, for example, semiconductor optical amplifiers (SOAs) or optical-electronics-optical (o/e/o) converters in both directions to extend the reach and split ratio from today's 20 km to 60 km and from 1:32 or 1:64 to 1:128, respectively. To reduce the ASE induced signal-to-noise ratio degradations in case of SOAs, the upstream ONU wavelengths might be restricted to a smaller wavelength range than defined today (e.g., to 1300–1320 nm). Special care has to be taken to cope with the bursty nature of the upstream transmission in order to avoid varying optical gains originating from different power levels and guard times between bursts. Also, the optimum positioning of optical or o/e/o repeaters has to be evaluated for different network layouts.

CONCLUSION

This article has outlined the current and next generations of PON technologies. While there are considerable differences between these systems, there are also striking similarities. This should be no surprise, as they share the same fiber medium and physical topology. Fundamentally, the differences amount to an issue of design style and base technology choice, rather than anything profound. Also, as experience has shown, all technologies have found their applications, and all are likely to coexist for the foreseeable future.

Most important, all of these systems have a similar set of requirements on the access cable facilities. Since the cost of deploying cables is by far the largest expense in any wireline network, it is critical to get it right the first time. And because all PON systems readily support the same outside plant, it means that network operators can deploy PONs today with one technology, knowing that someday they could migrate to another system.

As the deployment of PONs grows into the many millions of homes served, it can be seen that a new era of access networks is upon us. The 100-year history of the copper network is finally coming to an end, and the age of the PON has begun.

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BIOGRAPHIES

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