Options for Future Optical Access Networks

Russell Davey, BT; Junichi Kani, NTT; Fabrice Bourgart, France Telecom; Kent McCammon, AT&T Labs

ABSTRACT

Optical access technology is now standardized, commercially available, and being deployed in some countries. In general, technology continues to develop, and optical access is no exception. New optical access technologies are now being widely reported; the technical trends are WDM, 10 Gb/s, and longer reach/higher splits. It is also important to take account of the evolution from installed legacy in possible future optical access standards.

INTRODUCTION

Passive Optical Networks (PONs) are now taking off, and the primary focus of operators in the next few years will be how to support the large-scale deployment of PONs around the world in terms of creating services to exploit the Giga-Class bandwidth, and developing technologies to enable further cost reductions, fast and very extensive service offerings, and so on [1]. At the same time, operators need to consider the future migration from working PON systems to next-generation access (NGA) systems upon a PON fiber infrastructure. The driver for such an NGA system could be to provide even higher bandwidths than today's PONs in order to provide new services, or alternatively to further reduce the cost of delivering existing services. In either case, a smooth migration is sought that allows NGA to be deployed on the same fiber strand as a working legacy PON system such as Broadband Passive Optical Networks (B-PONs), Gigabit Ethernet Passive Optical Networks (GE-PONs), and Gigabit-capable Passive Optical Networks (G-PONs). In this article we describe commonly deployed PON fiber infrastructures around the world, review technology options for NGA, and discuss methods for upgrading a working PON to NGA.

Taking a quick review of previous PON standards, one can easily see three drivers: higher bit rates, higher service capability (including frame efficiency), and greater service integration. While ITU-T Recommendation G.982 (published in 1996) addressed time division multiplexing (TDM) narrowband services, ITU-T Recommendation G.983 series (B-PON) addressed triple-play services mostly implemented with a radio frequency (RF) video overlay, and ITU-T Recommendation G.984 series (G-PON) aimed at providing efficient triple-play service integration at the frame level, avoiding any local unnecessary protocol encapsulation as well as increasing the bit rate up to Gigabit Class. Table 1 summarizes these PONs standardized in ITU-T. GE-PON is also a Giga-Class PON standardized by IEEE, whose protocol is Ethernet native. Through the PON generations, the bit rates evolved by a factor of 50, peaking for the most popular G-PON line rate of 1.2 Gb/s upstream and 2.4 Gb/s downstream at an average 38 Mb/s downstream traffic capability per PON termination when deployed with a 64-way split. In fact, thanks to the efficient concentration and dynamic bandwidth allocation mechanisms embedded in the G.984 series, the actual service capability will be much higher.

All PONs are based around an optical line terminal (OLT) in the central office, which is connected to multiple optical network terminations (ONTs) in the customer premises via an optical distribution network (ODN) of fibers and passive splitters. Operators' investment in extending fiber to the customer premises was enabled by the lower fiber-infrastructure cost of a PON and the availability of cost-effective PON systems. An early international standard for a point-to-multipoint fiber infrastructure is found in ITU-T G.982 (11/1996), which defined the underlying ODN that PON transmission-system standards would later be based upon. The concept of attenuation range was established, which includes the minimum loss and the maximum loss of the ODN planned and constructed by the network operator. Since the cost of optics was strongly related to the attenuation range, three classes of ODN were specified to provide flexibility to support the range of ODN arrangements envisioned by FSAN group [2] for the multiple PON-based FTTx applications (e.g., FTTHome, FTTBusiness, FTTCabinet, and FTTCurb). Class A, B, and C ODN attenuation ranges were defined as 5–20 dB, 10–25 dB, and 15–30 dB, respectively, which in turn determined the dynamic range of the PON systems. Later, the first PON system (A-PON) was specified in ITU-T G.983.2 and further specified the ODN, including the following: supported split ratios of 1×16 and 1×32, ITU-T G.652 fiber type, maximum fiber reach of 20 km, 20 km differential reach (near ONT and far ONT may share the

	G.982	G.983 series (B-PON)	G.984 series (G-PON)
Protocol basis	Time-division multiplexing	Asynchronous transfer mode	Generic encapsulation method (GEM), derived from generic framing procedure
Bandwidth allocation	Static	Dynamic	Dynamic
ONTs per PON	16 min, 32 ready	32 min, 64 ready	64 min, 128 ready
Integration level	Narrowband dedicated	Broadband ISDN with WDM CATV overlay	Triple play through GEM with RF option
Downstream line rate(s) specified	N * 10 Mb/s (typical)	155 Mb/s or 622 Mb/s	1.244 Gb/s or 2.488 Gb/s
Upstream line rate(s) specified	N * 10 Mb/s (typical)	155 Mb/s	155 Mb/s, 622 Mb/s or 1.244 Gb/s

■ **Table 1.** *Generations of PONs standardized in ITU-T.*

same PON), and a minimum optical return loss of the ODN as seen from the OLT and ONT optical terminations. Operators would begin investing in the construction of PON networks as A-PON and B-PON became available and would follow the Class B ODN specifications originally outlined in the ITU-T G.982 and enhanced in the ITU-T G.983.2 Recommendation.

Class B ODN has since been constructed worldwide due to the three predominant PON systems. All are supporting Class B, including B-PON in ITU-T G.983.3, GE-PON (E-PON) specified in IEEE 802.3ah (PX-20 optics option), and G-PON in ITU-T G.984.2. However, Class B has meant that operators have had to choose between full reach to 20 km with reduced split and B-PON splitting ratio of 1×32 at reduced reach.

As optical component performance and cost have improved and operators have been seeking additional reach to lower infrastructure costs, Class B+ compliant systems featuring 28 dB maximum attenuation have become available. PON systems supporting Class B+ include enhanced B-PON in ITU-T G.983.3 Amendment 2 (2005) and the recent enhancement of G-PON found in ITU-T G.984.2 Amendment 1(2006), which has an attenuation range of 13–28 dB. The Class B+ increase in optical budget allows simultaneous full 20 km reach and 32-way split for nondispersion limited systems. Today, industry is converging on Class B+ systems and operators are building Class B+ ODN.

When PON line rates have increased to >1 Gb/s and dispersion penalties became a factor, PON standards added a 10 km reach option to allow wider line-width Fabry–Perot ONT sources. Operators have continued to strongly require a 20 km reach option to meet deployment requirements. Operators with a significant portion of loops beyond 10 km typically select only one variant and that has been the 20 km variant of ONT optics for single ONT inventory and installation.

Operators who have built a compliant ODN defined in the ITU-T G.98x series of Recommendations will require subsequent generations of PON systems to be deployable over legacy fiber investment, replacing the legacy OLT and ONTs without expensive changes to the ODN. Future PON systems supporting both 20 km and Class B+ ODNs provide the highest coverage of legacy PON migrations worldwide, since they are applicable to legacy ODNs built either to Class B or Class B+ and either 10 km or 20 km fiber distance variants of the standardized GE-PON, G-PON, and B-PON. New PON systems considered for migration on legacy ODNs must also consider optical return loss and resilience to optical reflections no worse than previously specified in legacy PON standards.

Another important aspect to consider in legacy ODNs is the distinctly different splitter arrangements used by operators and the corresponding different options for fiber rearrangements in the ODN. The choice of the splitter arrangement impacts the migration alternatives.

Standards-based PONs have been designed for wide flexibility in the splitting-to-distance trade-off and in the placement of splitter(s) between the OLT and ONT(s). Operators have selected different splitter arrangements with two common examples provided: the centralized splitter location and the distributed splitter approach with two (or more) stages of splitters in separate locations. The 1×32 overall split is the most common number of branches today, whether centralized with 1×32 splitters or distributed splitters consisting, for example, of 1×4 and four 1×8 splitters. Figure 1 illustrates these two common splitter arrangements.

The major PON standards are transparent to the specific splitter implementation such as the order of cascaded splitters or the splitter(s) distance to the OLT or to the ONT. For broadest applicability, NGA systems should be transparent to various splitters arrangements for the widest applicability to operators with varied legacy ODNs.

HIGHER-SPEED (10 GB/S) TDMA PONs

G-PON supports transmission line rates up to 2.448 Gb/s downstream and 1.244 Gb/s upstream. An option for NGA is to further increase the G-PON bit rates, with 10 Gb/s being a natural tar-
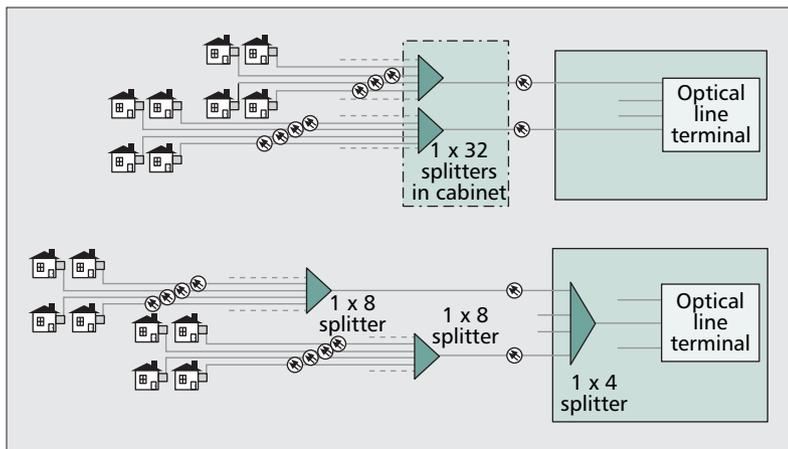
■ Figure 1. *Two common splitter arrangements: centralized 1 × 32; distributed 1 × 4 in the central office with multiple 1 × 8 in the field.*

get, since this is widely deployed in long-haul and metro networks. Research has begun on this [3–5] and the significant technical challenges which must be met are largely understood. Foremost among the challenges is to develop 10 Gb/s optoelectronics modules which can be manufactured in volume at costs appropriate for residential access deployment, that is, comparable to those achieved in G-PON today. While the primary target should be 10 Gb/s in both the upstream and downstream, it will be especially challenging to cost-effectively achieve 10 Gb/s in the upstream. This may lead to consideration of a lower bit rate in the upstream, depending on the capacity and cost per user of the ONT for the target applications (FTTHome, FTTBuilding, etc.), fiber reach, and optical budget.

At 10 Gb/s, for distances over 20 km, chromatic dispersion will not be negligible over the deployed ITU-T G.652-compliant fibers and measures must be implemented to counteract this. To allow smooth upgrades on a working PON, a 20 km minimum reach and Class B+ ODN should be supported. For reasons of cost, PONs are usually designed to minimize the performance of optical components in the ONT, and place higher-performance components at the OLT where their cost is shared among multiple customers. Applying this philosophy to a 10 Gb/s PON over Class B+ optics is likely to lead to consideration of signal processing, such as forward error correction (FEC), which was specified as an option in G-PON and GE-PON, but is likely to be an unavoidable feature in NGA high-bit-rate schemes. Optical amplifiers may also play an important role. The "bursty" nature of the upstream data in a PON will require the development of 10 Gb/s burst-mode receivers for use at the OLT. Clock and data recovery performance for the upstream may impact the TC framing efficiency through the lengthened overhead of upstream bursts. It will be necessary to efficiently map the full service range from narrowband voice services to very-high-speed burst-mode data transmission, thus requiring efficient bandwidth allocation mechanisms, real-time capability with limited transfer delay, jitter, and wander, as well as round-trip delays compatible with video channel switching.

Higher-speed PON may be applicable to coexist with most legacy PON system deployments on the same ODN pending the feasibility to support sufficient reach, Class B+ ODN, and use of a different wavelength allocation than legacy PON systems.

INCREASING REACH AND/OR SPLIT OF PONs

A typical PON deployment today would involve a maximum reach of 20 km with a split of up to 64. In line with this, the G-PON standard establishes industry best practice "Class B+" optical budgets of up to 28 dB for a system operating at 2.488 Gb/s downstream and 1.244 Gb/s upstream. This is the practical limit of PON optics today. In long-haul networks, optical amplifiers are widely used to extend the reach of systems to hundreds or even thousands of kilometers. The costs of optical amplifiers are now low enough that one could consider using them in a PON, especially since, in a PON architecture, the cost of the optical amplifier can be shared among all the customers on the PON. The protocols within the existing G-PON standard, known as the transmission convergence (TC) layer, would support a logical reach of 60 km and a logical split of 128, if the physical layer capability could be improved. A first step to consider is therefore using optical amplifiers to extend the physical reach and/or split supported by G-PON towards the limits of the existing TC layer, as shown in Fig. 2. The transparency of optical amplifiers means that they can equally be used for G-PON or GE-PON. Beyond this shorter-term possible application, optical amplifiers are a key enabling technology for next-generation optical access architectures in general.

From an operator perspective, there are several potential benefits arising from increasing the reach of PONs. Firstly, some customers are located at long distances from central offices — beyond the reach of G-PON today. Optical amplifiers are simple, low-power devices which could make them attractive to deploy at an intermediate location, so that G-PON equipment in the central office can be directly connected to these customers. Secondly, where customers are sparsely distributed over a geographical area, optical amplifiers can be used to ensure good utilization of the shared portions of the PON (i.e., the OLT and feeder fiber). Thirdly, depending on end-to-end network design, extending the reach of a PON can allow node consolidation, thus reducing the number of PON headend locations the operator needs to manage, and avoiding the need for a separate backhaul network tier to connect central offices to major switch/router nodes.

There are several choices of optical amplifier technology to consider:
• Erbium-doped fiber amplifiers (EDFAs)
• Thulium (for downstream) and praseodymium (for upstream) doped fiber amplifiers
• Semiconductor optical amplifiers (SOAs)

In metro and long-haul networks the EDFA is widely used since it provides excellent gain, power, and noise performance in the 1530–1565

nm wavelength window, and the range can be shifted to the longer wavelength band (e.g., 1570–1605 nm) by changing the design parameters; the 1550-nm window (e.g., 1530–1605 nm) corresponds to the minimum loss of optical fibers. When considering EDFAs to extend the budget of a PON, there are two issues to consider. Firstly, the existing PON standards use the 1480–1500 nm wavelengths for downstream transmission and 1260–1360 nm wavelengths for upstream, and both of these wavelength regions lie outside the 1530–1565 nm gain spectrum of EDFAs. To use EDFAs in a PON would therefore require additional transmitter options to be added to the standard within the gain spectrum of EDFAs. This would need to take account of the fact that existing PON standards allow the optional use of the 1550–1560 nm wavelength region for video broadcast. The second issue with regard to using EDFAs in a PON involves the fact that in a PON the upstream data are bursty. This is because the upstream operation of a PON relies on each ONT transmitting a burst of data when instructed to do so by the central OLT. So the upstream transmission of a PON consists of bursts of data, separated by gaps. Each burst can be of a different amplitude and slightly different wavelength. EDFAs operating with high output powers exhibit gain saturation effects, in which their gain is reduced. For metro and long-haul applications and the downstream direction in a PON, the data consist of continuous, uniform streams of Gb/s data and hence the EDFA gain does not react to the variations in the data stream. However, when the input power fluctuations occur on a timescale of ~10 μs to ~1 ms, as is the case in the upstream direction of a PON, then the EDFA can distort the burst causing problems. Techniques have been reported for achieving good burst-mode operation in an EDFA, but the details of these are outside the scope of this article.

While almost all commercial optical-fiber amplifiers have been EDFAs, alternative fiber amplifiers which operate in other wavelength regions are possible, although these have not to date been deployed in large volumes. Of particular interest with regard to a standard PON are praseodymium doped fiber amplifiers for the upstream and thulium doped fiber amplifiers for the downstream. For praseodymium fiber amplifiers, special techniques have been reported to deal with the bursty nature of the upstream data in a PON.

An alternative to fiber amplifiers is to use semiconductor optical amplifiers (SOAs), which are based on mature technology. While SOAs do not provide as good gain and noise performance as EDFAs, they have the advantages of being able to operate at any wavelength of interest and their gain dynamics are faster than EDFAs, so that they can more easily amplify the bursty upstream data in a PON.

As an alternative to optical amplifiers, electronic repeater technologies could be used to extend the reach of PONs and have been used to extend the reach of a G-PON to 135 km [6]. The electronics must be designed to accommodate the bursty upstream data; thus, this lacks the simplicity of the optical amplifier approach.
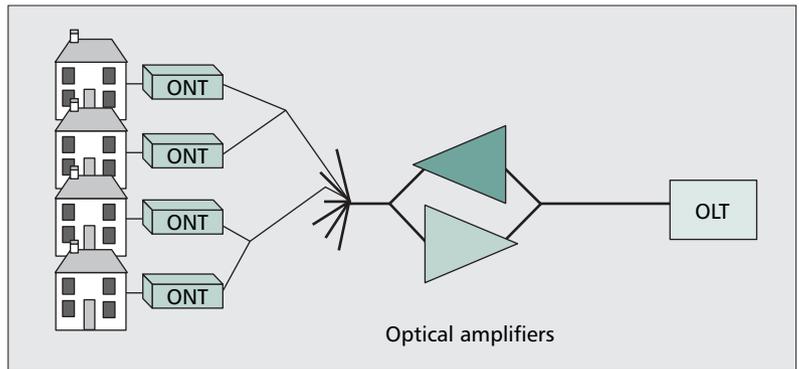
■ **Figure 2.** *Use of optical amplifiers at an intermediate location to extend the reach of a PON.*

Repeaters also tend to be bit-rate specific, making them less flexible than optical amplifiers for this application. However, repeaters have the advantage that they can allow wavelength conversion, which has benefits in extending the reach of a PON, and absorb the incoming bursts of optical-power differences, leaving only the clock recovery issue to the OLT receiver.

In addition to optical amplifiers, forward error correction (FEC) is another important technology for extending the capability of PONs. While FEC is specified in G-PON and GE-PON, enhanced versions of FEC could be used in future PONs to complement optical amplifiers. Early proof-of-concept experiments have shown that, by using optical amplifiers at an intermediate powered location, in combination with FEC, one could envisage a 10 Gb/s PON with 100 km reach and 1024-way split [3].

WDM PONS

CWDM AND DWDM GRID

G-PONs/GE-PONs already make some use of wavelength division multiplexing (WDM) to achieve single-fiber operation and allow the option of video broadcast via an overlay wavelength. Figure 3 shows how this is achieved.

On the other hand, long-haul and metro networks make extensive use of WDM; the typical number of wavelengths implemented in a system is eight to more than 100, depending on the applications. Therefore, it can be anticipated that the optical access networks will be evolved to exploit the large number of wavelengths in future.

Figure 4 shows the coarse WDM (CWDM) wavelength grid (ITU-T G.694.2) and the dense WDM (DWDM) frequency grid (ITU-T G.694.1) typically adopted in the long-haul and metro networks. The CWDM wavelength grid supports a channel spacing of 20 nm; this allows the use of uncooled (i.e., non-temperature-controlled) single-mode lasers, whose wavelength vary depending on temperature. For example, eight wavelength channels can be provided using CWDM in the wavelength range from 1471 to 1611 nm. When applying this concept to optical access systems, the impact on outdoor ONT modules, whose required temperature range is much wider than that of backbone systems, must be carefully considered.
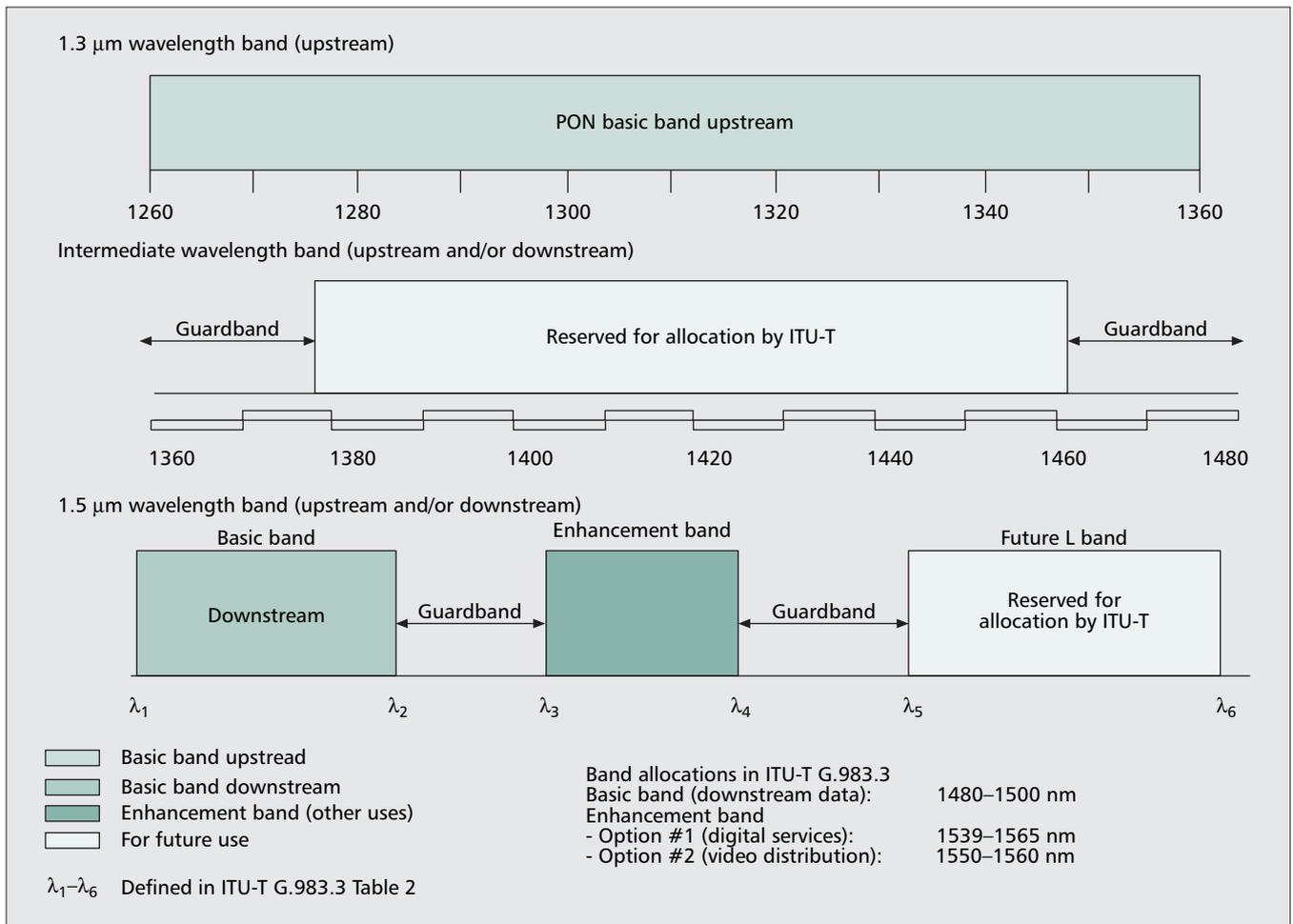
■ Figure 3. *Wavelength allocation in B-PON, G-PON and GE-PON.*

The DWDM frequency grid is anchored to 193.1 THz (equal to ~1552.52 nm). It supports a variety of channel spacings ranging from 12.5 GHz (~0.2 nm) to 100 GHz (~0.8 nm) and wider, and realizes systems with enormous numbers of wavelengths. DWDM is often used with EDFAs, whose amplification range is typically from 1530 to 1565 nm and can be shifted to the longer wavelength band (e.g., 1570 to 1605 nm), as mentioned in the previous section. DWDM using these two wavelength ranges with 100 GHz spacing provides 86 wavelength channels for example. Cooled (i.e., temperature-controlled) single-mode lasers are used as the transmitters and, in addition, wavelength lockers are needed for narrower spacings (e.g., under 50 GHz).
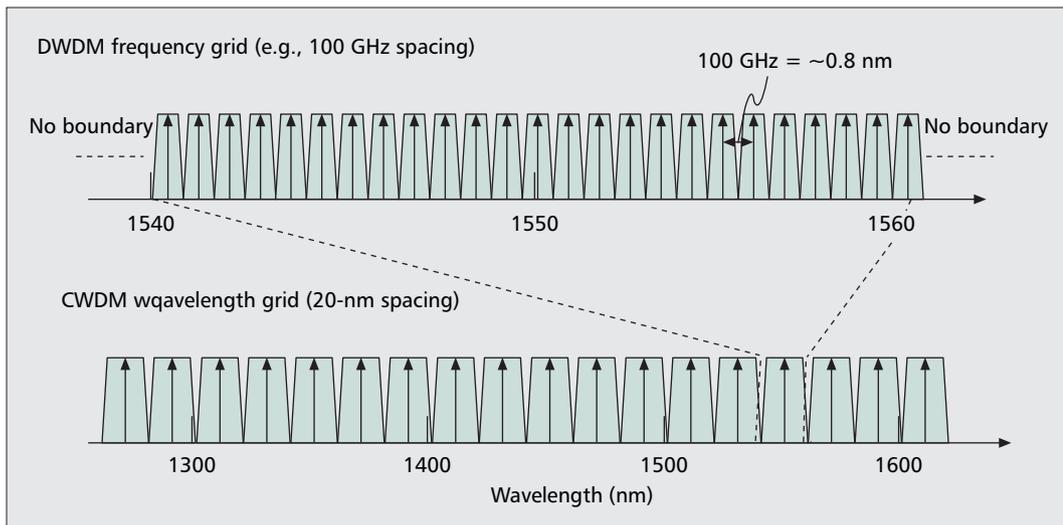
WDM Access and Colorless ONTs

An interesting application of many wavelength channels on PON is wavelength division multiple access (WDMA), in which each ONT utilizes a different wavelength from the others, as shown in Fig. 5. WDMA can provide a logical single-star topology over a physical passive double-star infrastructure to produce a very flexible network where a service to each subscriber can be configured and changed independently from the others.

If laser diodes with fixed wavelengths are used in WDMA, a range of wavelength-specific ONTs is required. This increases operational costs and decreases user friendliness. To make ONTs easy to use, they need to be identical yet capable of operating according to the wavelength plan. Such ONTs are called "colorless ONTs."
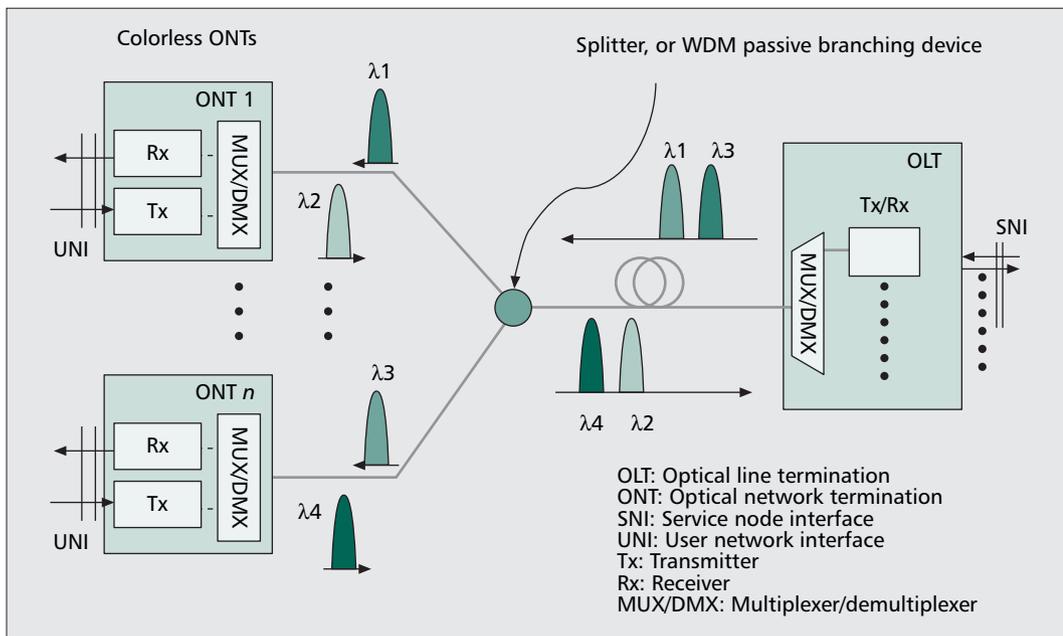
System technologies to realize colorless ONTs can be categorized into two types: one is a self-emission system and the other is a wavelength-supply system. In the self-emission-type systems, all ONTs basically have wavelength-selective or wavelength-tunable laser devices, and the transmitting wavelength of each ONT is configured when starting the service from the corresponding OLT. In wavelength-supply-type systems, a continuous spectrum from the OLT is demultiplexed at a wavelength-selective branching device so that a unique wavelength is supplied via a separate fiber to each ONT. The ONT either modulates the selected wave with a signal [7] and returns it upstream, or a laser diode in the ONT locks to the supplied wavelength [8]. The signal from this laser may then be modulated for upstream transmission.

Hybrids of the traditional TDMA used in G-PON and WDMA have also been reported [9]. Code division multiple access (CDMA) has also been researched as an alternative to or as a complementary WDMA method for realizing a flexible access network [10].

■ Figure 4. *DWDM frequency grid and CWDM wavelength grid.*

OLT: Optical line termination
ONT: Optical network termination
SNI: Service node interface
UNI: User network interface
Tx: Transmitter
Rx: Receiver
MUX/DMX: Multiplexer/demultiplexer

■ Figure 5. *An example of WDM access on a PON.*

UPGRADING A WORKING PON TO NGA

The previous sections have reviewed technological options for NGA: 10 Gb/s, WDM, and longer reach/higher splits. This section discusses upgrading a working PON to NGA.

While moderate increases in the capacity of a deployed PON can in some cases be achieved by ODN rearrangement, in general, for more significant increases, either additional fiber installation or deployment of an NGA system over the installed fibers will be required. Operators can incrementally invest in additional fibers or fiber ducting for future new systems in order to complement a deployed PON system and provide for future new services and higher capacity demands to subscribers. Upsizing cables at initial construction to provide a second fiber from OLT to each and every ONT can add considerable cost.

For scaled deployment of a residential PON, such an oversizing would represent a large investment. We therefore expect "fiber-lean" PON deployments to be a common legacy situation for operators. In such a situation, WDM can be used to migrate users on the working PON to NGA.

WDM enhancement of an existing ODN is already described in the current PON standards. Figure 3 shows the ITU-T G.983.3 B-PON, as decided in 2001, with an operating wavelength of 1480–1500 nm (downstream) and 1260–1360 nm (upstream); this wavelength allocation has since been adopted for G-PON and GE-PON. Two enhancement band options are specified, either for video distribution (1550–1560 nm) or for additional digital services (DWDM wavelengths within 1539–1565 nm). The downstream PON laser allocation was narrowed from 1480–1580 nm (specified in ITU-T G.983.1 in 1998) to

A "fiber–lean" situation is likely, and so NGA should be able to coexist on the same fibers as a working legacy PON. This can be achieved by taking a wavelength enhancement band approach in which NGA operates at different wavelengths to the legacy PONs.

1480–1500 nm, at wavelengths well above any elevated loss from water absorption in legacy fiber cable. A key objective of this wavelength reallocation was to reduce the bandwidth used by the downstream PON laser and move it away from the erbium band, which was needed for optical amplification of overlay signals in the newly specified enhancement band. A wide guard-band was deemed necessary between the basic band and enhancement so as to ensure a low-cost filter implementation in the price-sensitive ONT. The NGA wavelength allocation is to be specified in an enhancement band and/or a future band (Fig. 3) so as to allow coexistence on the same fibers as legacy B-PON, G-PON, or GE-PON, which share a common wavelength allocation. Further study of the enhancement of and future band-wavelength allocation is needed to achieve low-filter cost at each ONT location and to maximize the spectrum for NGA applications.

Before NGA is deployed on an existing PON, the terminal locations for dropping or inserting new wavelengths must be prepared. At the OLT side, an in-line passive WDM device must be inserted either at the time of the initial ODN build, to avoid legacy PON service disruption, or at a later time with a short service outage. An additional optical margin needs to be allocated for such filter insertion loss on the OLT side of the splitter. To avoid NGA systems interfering with legacy PONs which coexist on the same fiber, a WDM filter within the legacy ONT should be designed to block the NGA wavelengths. If this is done, then legacy PON and NGA PON can coexist on the same fiber and customer ONTs can be individually migrated to an NGA system without affecting other users' services. Alternatively, a three-port WDM device could be installed at ONT location(s) to allow a customer is to receive both the new NGA and legacy PON services. For ONTs deployed with broadband photo detectors without a WDM blocking capability, WDM migration becomes operations intensive, since every ONT location must be visited to add an in-line WDM blocking filter before new wavelengths may be added to a legacy PON.

CONCLUSIONS

PON standards are now mature and deployments of B-PON, GE-PON, and G-PON are taking place. In parallel, new PON technology continues to be developed. A next-generation access (NGA) system can today be envisaged as a PON using some or all of the following technologies:
• WDM
• 10 Gb/s
• Longer reach and higher splits

The optimum design of NGA will be determined by a combination of evolving service requirements and technological advances. Whatever design of NGA emerges, it will be important for operators to be able to migrate a working legacy PON to NGA. A "fiber–lean" situation is likely, and so NGA should be able to coexist on the same fibers as a working legacy

PON. This can be achieved by taking a wavelength enhancement band approach in which NGA operates at different wavelengths to the legacy PONs.

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BIOGRAPHIES

RUSSELL DAVEY (russell.davey@bt.com) graduated in physics from Oxford University in 1989. He holds an M.Sc. in telecommunications eengineering from University College London and obtained a Ph.D. from Strathclyde University in 1992 for research into mode-locked Erbium fiber lasers. He joined BT in 1994 and was heavily involved in the first application of WDM in the BT network. Since 2001 he has managed BT's research activities in optical access systems and is a regular speaker on this topic at international conferences.

JUNICHI KANI is a research engineer in NTT Access Network Service Systems Laboratories, NTT Corporation, and has been participating in ITU-T and the Full Service Access Network (FSAN) initiative since 2003. He has been engaged in research and development of WDM-based optical networks/systems for metro and access applications for 10 years in NTT, and has received five conference awards in this field. He has B.E., M.E., and Ph.D. degrees in applied physics from Waseda University, Tokyo, Japan.

FABRICE BOURGART joined France Telecom R&D in 1987 after graduating in telecommunications engineering at ENSEIRB, Bordeaux, France. He began working on the PON concept, which later led to the G.982 standard. He has since worked on different PON technologies' development, ranging from optoelectronics to management aspects implied by the PON concept with France Telecom's network planning, and among EURESCOM and lately FSAN work groups.

KENT MCCAMMON currently leads AT&T's development of technical requirements for G-PON. His focus has been optical design, transmission, and testing of PON systems since the first AT&T deployment in San Francisco in 2002. He has been active in developing common optical layer standards for PON systems by participation in FSAN, ITU-T, and IEEE. He currently serves as chair of the FSAN OAN-WG. He received his undergraduate and graduate degrees at California Polytechnic University at San Luis Obispo.