Next-Generation PON—Part III: System Specifications for XG-PON

Frank J. Effenberger, Huawei Technologies
Hiroaki Mukai, Mitsubishi Electric Corporation
Jun-ichi Kani, NTT Corporation
Michael Rasztovits-Wiech, Nokia-Siemens Networks

ABSTRACT

With the knowledge that XG-PON is of primary interest to service providers as their preferred next generation optical access system, the investigation next turns to determining its technical specifications. This article presents the current thinking on the XG-PON systems. It presents a rough outline of the system design for the wavelength plan, the power budget, the protocol, and the management and service model. This work is likely to be the basis for standardization in upcoming ITU-T recommendations.

INTRODUCTION

As introduced in the previous companion articles, there is a strong interest in defining the next generation of passive optical network (PON) systems that are compatible with the current G-PON [1–6] and E-PON [7] systems. Furthermore, it appears that XG-PON systems are the best candidate for standardization. This final article more fully develops the technical specifications of the XG-PON systems.

The content of this article is organized as follows. In the next section we consider the wavelength plan of XG-PON systems in the coexistence setting, considering the wavelengths that have already been utilized by other systems, and conclude with a summary of the wavelength plans selected for the various XG-PON systems. We then briefly consider the issue of power budget detailed requirements. We then present the major concepts of the transmission convergence design for XG-PON1, breaking this topic down into the framing, service adaptation, and PHY adaptation layers. We also discuss two possible ways forward for the XG-PON2 TC layer. We then discuss the ONU management and service models that can be employed. The article then concludes with a summary of major points.

WAVELENGTH PLAN

XG-PON1

Under the assumption that all the requirements mentioned in the companion articles are met, we arrive at the spectrum illustrated in Fig. 1. The downstream wavelength band of 1575–1580 nm is used, since it is the only wavelength band that is left in the system with video overlay and where the fiber window is limited to 1580 nm. This choice has the added advantage that it also matches the downstream wavelength selection included in P802.3av draft standard.

The following part discusses five upstream channel assignments:

- Within the L-band :1595–1615 nm (channel A)
- Within the C-band: 1539–1559 nm (channel B)
- A video-compatible C-band: 1530–1540 nm (channel C)
- O-plus band: 1340–1360 nm (channel D)
- O-minus band: 1260–1280 nm (channel E)

The choice of channel could be dictated by the particular deployment scenario in question; however, no choice is fully satisfactory.

Channel A puts new requirements on the deployed fiber, splitters, and connectors (i.e., operation at wavelengths up to 1615 nm), and the guard band between upstream and downstream is only 15 nm, which makes adequate isolation between these channels in the ONU extremely difficult to achieve.

Channel B does not support a radio frequency (RF) video overlay.

Channel C appears ideal; however, it is not feasible. The guard band for the G-PON system begins at 1530 nm, and the guard band for the video overlay system is currently unspecified, but presumably is around 1540 nm. The isolation requirements for the next generation (NG)-PON1 upstream are initially thought to be relatively easy (~1 dB of S/X is required for G-PON/NG-PON rejection, and perhaps ~15 dB of isolation for video/NG-PON rejection), but the lack of tight specifications on the existing G-PON ONU optics makes this choice risky. In addition, such a narrow band makes transmitter for channel C compatible optical network units (ONUs) expensive.

Channel D and E both would not be compatible with the wavelength-division multiplex 1 (WDM1) filter specified in G.984.5. The new filter that would be needed is likely to have some additional loss in comparison. In particular, channel D looks to be quite bad in this regard, requiring three filter elements, and Channel E requires two, while the original WDM1 designs requires only one filter element.

Considering the above observations, the choice is narrowed down to either the L-band (channel A) or the O-minus band (channel E). Table 1 provides further comparison between these two assignments, to conclude that the upstream wavelength would use channel E.

Note that the downstream window is only 5 nm wide, and will require cooled laser sources. It is conceivable that this downstream band could be extended beyond 1580 nm for systems that operate on more modern ODN infrastructures, and this could enable optical line termination (OLT) optics suitable for outdoor deployment, or uncooled operation in an indoor deployment. However, such extension must be small, otherwise it will complicate ONU filter design. The upstream window is 20 nm wide, enabling the use of uncooled laser sources under all circumstances, saving on ONU optics costs.

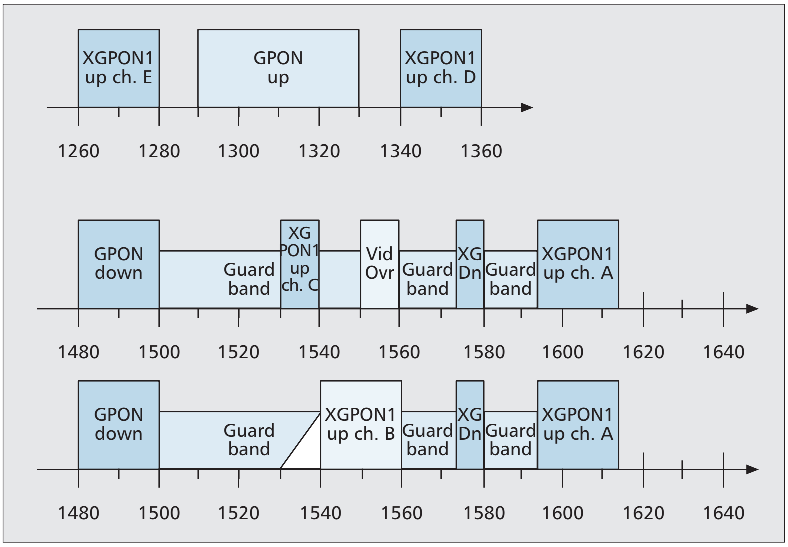

Figure 1. *XG-PON1 basic wavelength plan options.*

Extended Reach and Wavelength Controlled XG-PON1

An extended practice recommendation for XG-PON1 wavelengths is also envisioned. This specifies 0.5 nm wide wavelength windows that are based on the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) dense WDM (DWDM) grid, as shown in Fig. 2. What is illustrated is a 200 GHz channel spacing, which was chosen to reduce cost. Smaller channel spacings also in line with the ITU grid are possible. It should be noted that the D4 subchannel falls outside the regular downstream XG-PON1 wavelengths, so the use of this channel would require the slight adjustment of the band edge to 1581 nm. The extended practice could be used in various ways. First, just one of the wavelengths could be used to allow optically pre-amplified receivers to use narrowband filters to improve their sensitivity. Second, four wavelength pairs could be used to multiplex four logical PONs onto a single fiber, both for the entire PON section, or only the feeder fiber.

Application of the extended wavelength plan is for further study.

XG-PON2

Under the assumption that WDM/TDMA or WDM/WDMA coexistence for the XG-PON2 system is used, and further, that XG-PON2 will also comply with the maximum wavelength of 1580 nm, spectrum availability substantially similar to that of the XG-PON1 is obtained. The downstream band is the same as for XG-PON1, achieving specification commonality and potential component reuse. The upstream band spans 1260–1280 nm. This O-band placement permits the use of directly modulated lasers without excessive dispersion penalty, and the spectrum band width permits the use of uncooled lasers.

Hybrid DWDM/XG-PON

The channel spacings for hybrid DWDM/XG-PON can be selected at either 100 GHz or 50 GHz. As can be seen above, there is not much wavelength space available; therefore, it seems reasonable to choose between 8 channels with 100GHz spacing and 16 channels with 50 GHz spacing, which correspond to a 7 nm wide band. Hybrid DWDM/XG-PON requires C-band upstream allocation because it is sensitive to the fiber loss for upstream, but this requirement is in conflict with the video overlay, which presents serious compatibility issues. For the downstream wavelength, hybrid DWDM/XG-PON could operate from 1575 to 1582 nm.

Hybrid DWDM/XG-PON is for further study.

Wavelength Plan Summary

The overall wavelength plan is shown in Fig. 3. This plan pulls together the diverse set of requirements from the PON deployments and NG-PON system concepts into a minimal set of wavelength assignments. It also coincides with the wavelength plan of the 10G-EPON, which might result in good volume economics.

Power Budget

This section briefly reviews the power budget requirements for XG-PON1. The main focus of standardization will be placed on developing a basic practice for the XG-PON1 system, and then to develop extended practices for both the XG-PON1 and XG-PON2 systems.

There is a relationship between the power budget and the protocol layer, because the protocol layer may offer some level of FEC. This can reduce the required transmitter power, or make the receiver construction simpler and

Consideration	Channel E (O-minus)	Channel A (L-band)	Comments
Optical component commonality with IEEE P802.3av 10G-EPON	Yes	No	Possible economies of scale may apply to XG-PON2
Relative cost	Diplexer filtering easier	Lower laser efficiency	Conflicting evidence on relative cost
XG-PON1 optical component availability time frame	Quicker	Longer	L+ band lasers have lower slope efficiency and are more challenging.
Fiber loss impact on power budget	Loss is higher	Loss is lower	Lower loss in L+ band may be offset by lower available laser power
Compatibility with legacy PON ODN (fibers)	Yes, but higher line losses	Yes, but concern about higher bending loss	Respective risks depending on plant qualification and engineering process
Compatibility with G.984.5 (WDM1 filter)	No	Yes	O– requires revision of G.984.5 and has higher loss on legacy PON path
Compatibility with OTDR monitoring @ 1650 nm	Yes	No	May be an important consideration for some operators
Dispersion penalty for long reach	None	Insignificant	For XG-PON1 line rates
Reach extenders friendly	Possible	Possible	
Coexistence using TDMA	Easier	Harder	10 Gb/s upstream in L-band requires reduced chirp lasers or dispersion compensation
XG-PON1 overlay friendly (DWDM extension)	For further study	For further study	DWDM components and colorless concept investigated in L band

Table 1. *Wavelength selection criteria table for XG-PON1.*

therefore cheaper. This will have to be coordinated between the two efforts.

For XG-PON, there will be two loss budgets, which are denoted here *Normal* and *Extended*. At a minimum, the Normal loss budget is defined as commensurate with a Class B+ loss budget plus insertion loss (including the loss of one connector) from WDM1. It is intended that an existing ODN designed to a Class B+ loss budget for GPON application will also support an XG-PON system designed to the Normal loss budget. The link loss for XG-PON1 will be approximately 28.5 to 31dB at BER of 10^{-12}. The Extended loss budget is defined as being commensurate with a Class C+ loss budget plus insertion loss (including one connector) from WDM1. It is intended that an existing ODN designed to a Class C loss budget for GPON application will also support an XG-PON system designed to the Extended loss budget. Exact values for each loss budget are for further study.

Framing and TDMA Control of XG-PON Transmission Convergence Layer

The standardization of the transmission convergence (TC) layer for the XG-PON draws many diverse opinions, for the reason that, unlike the physical layer, there is little that strictly limits the protocol design. However, the discussion participants have agreed that reusing or adapting an existing protocol system is advantageous.

This section discusses framing and time-division multiple access (TDMA) control for XG-PON, based on extensions of G-PON TC. It is also noted that the IEEE P802.3av Task Force has been working to extend 1G-EPON to 10 Gb/s rates [8]. Opportunities and methods for convergence between XG-PON and 10G-EPON are for further study.

XG-PON1 with 10 Gb/s Downstream, 2.5 Gb/s Upstream

It has been agreed that the TC layer of the XG-PON1 system will be essentially based on the G-PON TC protocol. The new XG-PON TC layer protocol (XGTC) will accommodate:

- Existing architecture simplifications that have been introduced in G-PON since the initial approval of the standard (e.g., deprecated asynchronous transfer mode [ATM] support)
- The increased service demands in NG-PON (i.e., more ONUs, more users per PON)
- Cost-efficient implementation of the increased speed
- Other features among being discussed that allow to improve the performance and reduce implementation complexity

On the other hand, some enhancements of the G-PON protocol can be envisioned. For example, the PLOAM channel could be made more flexible by allowing for multiple messages in the same frame. The length of the message will likely be extended, so that all the communications that currently require several PLOAM messages can be accomplished with a single message. The message acknowledgment system can also be improved.

Conceptually, the XGTC layer can be viewed as composed of three sublayers: the service adaptation sublayer, the framing sublayer, and the PHY adaptation sublayer. The service adaptation sublayer operates with the concepts of XG-PON encapsulation method frame (XGEM frame) and XGEM Port-ID, and support the functions of service data unit (SDU) (user data frame and OMCI traffic) fragmentation and reassembly, XGEM frame delineation, and XGEM port-ID filtering. The framing sublayer is concerned with the structure of the 125 μs XGTC frame; it supports the functions of XGTC frame/burst encapsulation and delineation, embedded operations, administration, and maintenance (OAM) processing, physical layer OAM (PLOAM) transport, and Alloc-ID filtering. The PHY adaptation sublayer encompasses the matters of forward error correction (FEC), line coding, and burst mode overhead.

Compared to the two-sublayer GTC protocol suite, PHY adaptation has been identified and made separate from the framing sublayer to reflect the need for clean delineation between the two groups of functions.

From simplified implementation, it has been suggested that the protocol should use a data unit larger than octets. The most popular width for 10 Gb/s systems is 32 bits, as it results in a data path operating at 311 MHz, which is well within the capability of many existing logic devices. Therefore, it has been agreed that XGTC layer follow the principle of a 4-byte word alignment, which impacts primarily the Service Adaptation and Framing sublayers. This could produce a new protocol: XG-PON TC, which is specifically designed for the 10 Gb/s application. The following figures provide an illustration for such a development.

XGTC Framing Sublayer — Along with the word alignment, to support the increased service requirements, the XGTC protocol must enlarge certain fields to make the code space larger for the quantities that those fields represent. Namely, the ONU-ID and the XGEM Port-ID need expansion. There have been several proposed minimal changes that expand both of these fields to 2 bytes each.

Figure 4 shows one proposed format of the XGTC downstream frame format. Notably, the PLOAM and BIP are enlarged to the next 4-byte boundary. The extra space in the PLOAM message allows for increase in the ONU-ID address space to 16 bits (64K ONUs), and the larger BIP maintains the saturation bit error rate. Multiple PLOAM transmissions are also possible. Changes to bandwidth map are less obvious — now they indicate starting and stopping word boundaries, and not byte boundaries. In addition, the way that the bandwidth map pointers relate to the operation of FEC will likely be changed, where pre-FEC data payload would be indicated, rather than the post-FEC payload as currently done in G-PON.

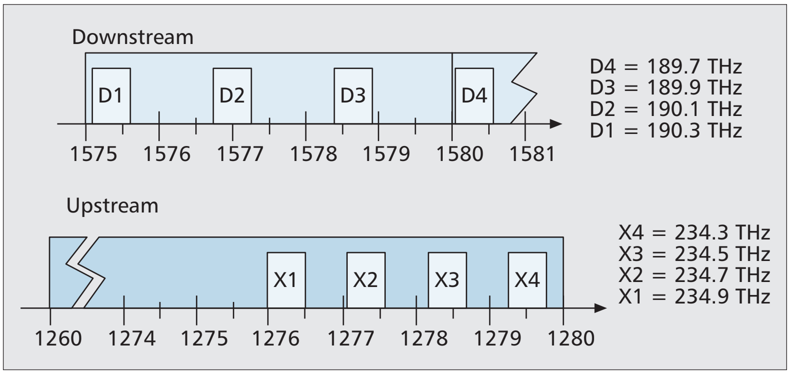

Figure 2. *XG-PON1 extended wavelength plan.*

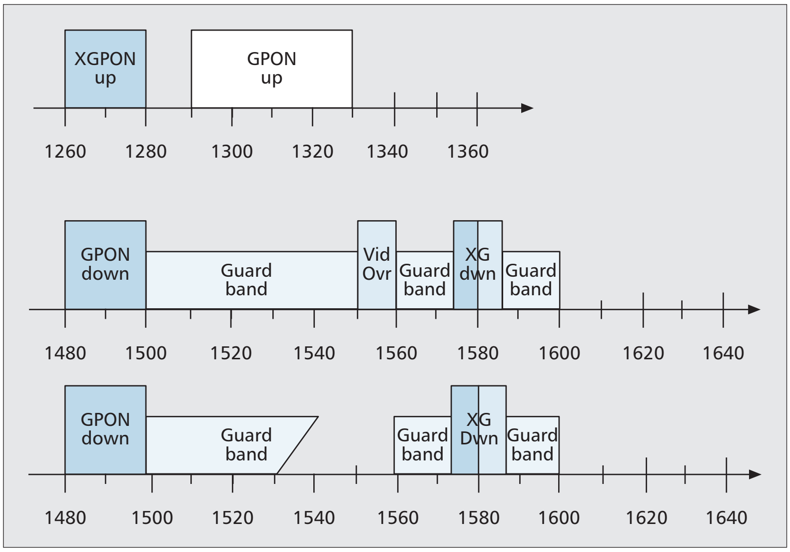

Figure 3. *The NG-PON1 spectrum plan.*

It is also possible that the PLOAM channel itself may be further upgraded. The length of the PLOAMd field may be changed so that all the communications that currently require several PLOAM messages can be accomplished with only one, thereby making the PON protocol simpler and faster.

In addition, the PLOAM channel could be made more flexible by allowing for multiple messages in the same XG-PON1 downstream frame, reusing the G-PON Alen field mechanism to indicate the number of PLOAM messages in the frame. This could make the PLOAM channel more responsive, and this could be important for power saving features.

For another example, the provision of a real time clock synchronization feature could be built into the TC layer. It is possible to combine this function with the framing signal itself.

Figure 5 shows the existing G-PON upstream frame structure and the proposed XG-PON1 extensions. Similar to the downstream, all fields are increased accordingly, to fit the 4-byte boundaries. Additionally, the definition of the contents of the DBRu could be modified, to change the granularity of the bandwidth request to 4 byte words, and to drop the nonlinear lossy compression algorithm that G-PON uses.

As in the downstream direction, the size and

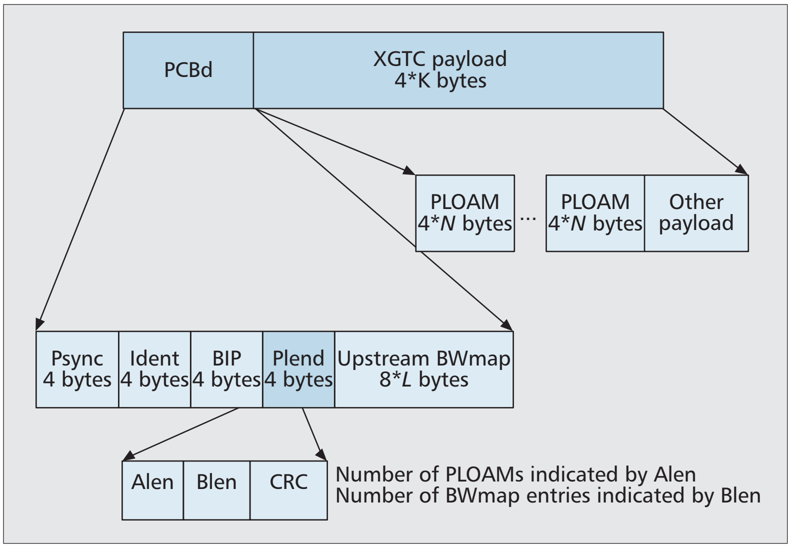

Figure 4. *An example XG-PON1 downstream frame format.*

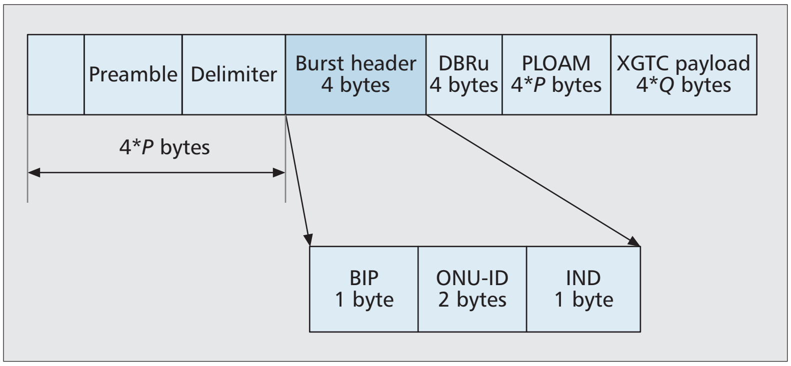

Figure 5. *An example XG-PON1 upstream frame format.*

structure of the PLOAMu field can be further modified; however, once specified, the overall size of the PLOAMu field should remain fixed to keep the bandwidth allocation simple.

XGTC Service Adaptation Sublayer — Figure 6 shows modification to G-PON GEM format, focusing on 4-byte alignment. The existing 5-byte-long header is extended to 8 bytes, which provides several benefits. The Port-ID, payload length, and PTI fields could each be extended to 2 bytes, giving more flexibility. The current 13-bit HEC could be reused, or a new larger and stronger HEC could be devised. Indeed, there is enough space to contemplate adding additional features to GEM encapsulation that would aid in the reception of the user data, such as a protocol ID, sequence number, or encryption data (a key index for key switch). But more importantly, the alignment of the 8-byte header to the presumed data transfer clock will hopefully reduce the troubles that some implementations have experienced with back to back GEM fragments.

Figures 4–6 depict the TC frame, which would be operating at a nominal data rate of 9.95328 Gb/s downstream and 2.48832 Gb/s upstream. There are numerous possibilities on how the TC frame would be adapted to the physical layer. Line-code selection and FEC code selection represent two major choices to be made at this time, including decision whether to use sub-rating or super-rating.

XG-PON PHY Adaptation Sublayer — The simplest line code is the non-return-to-zero (NRZ) code, coupled with a scrambler to ensure statistical DC balance. This is very efficient, and has been shown to work well continuous mode systems. Concern has been expressed that certain pathological bit patterns can spoof the frame synchronous X7+X6+1 scrambler used in GPON, giving rise to possible threat denial-of-service attacks; this issue is for further study. In burst-mode systems, a special receiver is required to efficiently detect NRZ code. Such receivers are widely deployed in at the 1.25 Gb/s rate for GPON, and by the time XG-PON systems are anticipated to be deployed, 2.5 Gb/s data rate receivers should be available. Therefore, the scrambled NRZ line code is selected for application in XG-PON1 in both the upstream and downstream directions.

In terms of FEC code, the choice must balance the benefits of signal gain and the cost of bandwidth occupied for parity as well as computational complexity of mediu access control (MAC) devices. The trade-offs for the downstream and upstream may be different, and it is not clear at this point which FEC code(s) will be selected. The exact choice of code is made mainly to match the line rate of the TC layer with the desired line rate of the link.

The FEC code raises questions on how to adapt the TC-layer rate relative to the link rate. One possibility would be to sub-rate the TC-layer, so that it runs slower than the nominal line speed. The alternative would be to super-rate the optical link, which then allows the TC-layer to operate at the nominal rate. It could also be noted that hybrid schemes are possible that both sub-rate the TC-layer and super-rate the optics at the same time.

All the other features of G-PON would presumably be maintained in the NG-PON TC layer. In particular, the first companion article specifies many of these feature capabilities, such as the support of consumer and business applications. NG-PON is required to extend the service models to support the whole G-PON DBA system, including the priority based Diffserv-like model as well as the rate controlled model to support residential and business applications on the same PON and even the same ONU. For each *service category* (e.g., residential or business) there is a need for a minimum of 4 T-CONTs. Note, this description assumes to reuse the G-PON TC protocol principles to give a clear guidance.

XG-PON2 WITH 10 GB/S SYMMETRICAL

The FSAN community has not achieved consensus as to the direction for XG-PON2. Some see a natural progression from G-PON to XG-PON1 to XG-PON2, with minimal changes in the framing, TC, and management protocols. Others see the 10 Gb/s upstream as a point for transition to the 10G-EPON standard. This remains a subject of ongoing study.

Extend XG-PON1 to 10 Gb/s Upstream — The obvious solution is to retain the 10 Gb/s downstream path as implemented in XG-PON1 and to extend the framing structures for the TC layer specified in the XG-PON1 section to support 10 Gb/s upstream. This would allow for XG-PON1, XG-PON2 and G-PON co-existence on the same PON and would allow the reuse of the all of the basic data structures. However, it is not clear if fragmentation should be supported in the upstream at these rates and what impacts that would have on the DBA algorithm envisioned for NG-PON1 systems. In addition, separate ranging windows maybe required for XG-PON1 and XG-PON2 to allow the dual rate receiver at the OLT to prepare for the reception of a specific burst at the correct bit rate.

P802.3av for XG-PON2 — If XG-PON2 follows the 10G-EPON system in some fashion, we then must address the notable gaps in this standard. The XG-PON2 work in the ITU would attempt to fill them. These uncovered topics include: activation, security, protection switching, dynamic bandwidth allocation, and management (dealt with in the next section), which are out of scope of IEEE P802.3av/former P802.3ah standards.

The current P802.3av draft contains an accommodation for this kind of extension. The MAC-control channel was given a new extensible message type, which can be used by the ITU to define the few extra messages that will be needed to implement the missing functions that are appropriate for the fast and low-level MAC-control channel.

P802.3av specifies only the physical layer. In various ways, some of those missing functions can be fulfilled. The following are some of the possible solutions:

Activation: In the Ethernet environment, IEEE802.1X is specified as the authentication protocol. It can be applied to the ONU authentication in PON system.

Security: In the Ethernet environment, IEEE802.1AE is specified as the security function. It can be applied to the secure channels secure channels between the OLT and the ONU at the expense of bandwidth due to the overhead of the protocol.

Protection switching: In ITU-T G.984.1, Type-B PON protection configuration and Type-C PON protection configuration are defined. Type-B protection switching requires a fast ranging procedure such as POPUP, as well as immediate (as low as 500 µs or four consecutive frames) detection of a fault on the ODN. To achieve it in the EPON system, a similar definition of a MAC control function needs to be implemented. On the other hand, Type-C PON protection switching is actually a packet by packet switching. In an EPON system, Ethernet linear protection switching protocol defined in ITU-T G.8031 can act as Type-C protection switching, when the protecting routes are configured between the OLT and the ONU.

Bandwidth allocation: With P802.3av systems, the concept of the logical link is the entity which unifies the ONU, T-CONT and GEM port in GTC. Bandwidth allocation can be done per logical link. The P802.3av system supports up to 32K unicast logical links.

Management: Currently, G.984.4 OMCI over Ethernet P2P is being discussed in ITU-T. By extending this idea to P2MP Ethernet, the difference between GTC and EPON can be eliminated from the management point of view.

Power saving: Currently, power saving protocol with PLOAM is being discussed in ITU-T. Extending this protocol to the MAC control channel, the same function can be added to the EPON system.

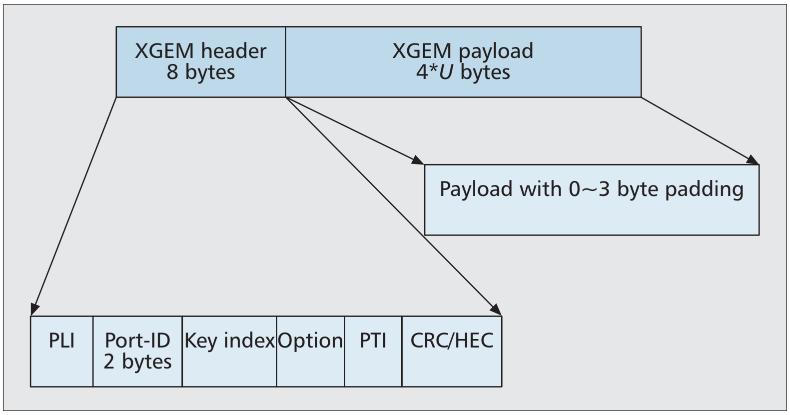

Figure 6. *The XG-PON1 XGEM format.*

ONU Management and Service Models in XG-PON

ONU management is the most complex part of the PON system, as illustrated by the size of G.984.4 (the revised OMCI Recommendation), as compared with the other standards in the G.984 series. This material has grown to such a size that many have advocated that it be limited in some respect. With this thought in mind, it is useful to consider the multiple management systems that can be brought to bear on XG-PON, and to propose the scope of each system and how they relate to each other.

In the PON system, there are three broad layers of interaction that could be called management:

The first management layer is associated with the physical and TC layer, and is mediated by low-level mechanisms such as embedded management using the protocol fields in TC frames exchanged by the OLT PON MAC device and the ONU PON MAC device (in the case of G-PON, this includes the FEC, DBA, and security fields in the GTC layer), and the PLOAM messaging channel. In the case of EPON, this consists entirely of the MPCP messaging channel. This layer is used only for the media access functions, for functions that require very fast or localized actions, and to set up the next layer channel.

The second management layer is associated with an out-of-band channel that connects the OLT system and ONU system. In G-PON this is

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the OMCI, while in EPON there is a basic OAM cannel and extending this channel is not currently standardized (although some proprietary systems do exist.) This channel is used to implement a full FCAPS management capability for the ONU. However, as mentioned before, the scope of this channel is being limited to *layer 2 and below* functions. This boundary is fuzzy, and there are exceptions; however, it sets the basic framework for the management system.

The third management layer is associated with an in-band channel that connects the ONU system with an element management system (called auto configuration server) deeper in the service providers' network(s). This could include SNMP, TR-69, or ACS systems. Work in the DSL Forum's WT-142 is establishing the scope and framework for TR-69 for G-PON, and WT-155 is defining the TR-69 MIB for G-PON.

In a related topic, in order to manage a device as complex as an ONU, the service model needs to be specified, because so much of the managed entities and attributes relate to the services and how they are provided. Currently, work in the Broadband Forum's TR-156 [9] and WT-167 is defining the service models only for data services. This work revolves around the usage of the PON constructs of T-CONTs and GEM Port-IDs to create logical connectivity for VLAN-tagged service flows. BBF is currently working to extend the model to full services.

SUMMARY

This article reviews the specification development progress that has been achieved for the XG-PON system. The basic wavelength plan for the XG-PON systems (both asymmetric and symmetric) has been developed where the downstream operates at 1577 nm and the upstream operates at 1270 nm. An extended wavelength plan consisting of four DWDM wavelengths defined in each band has also been defined. The hybrid DWDM scheme remains for further study. The power budget has been defined to a certain level; however, achieving full coexistence without any penalty on the existing G-PON system is difficult. Even more difficult is doing so at an XG-PON cost that is economically feasible.

The protocol for XG-PON has been defined at a very high level. The basic ideas are that the protocol would look similar to that of G-PON, which implies it will use 0.125 ms periodic framing, it will have a bandwidth map, and it will use gigabit encapsulation method for data transport. The protocol will also be word aligned to simplify implementation. Many small improvements, simplifications, and new features are being considered for the XG-PON protocol layer.

The ONU management interface for XG-PON will use the same definition as G-PON. Moreover, the service models and all the other details that define the typical and well-tested implementations in G-PON will be inherited. The hope is that the significant progress that has been made in G-PON system maturity and interoperability will apply transparently to XG-PON as well.

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BIOGRAPHIES

FRANK J. EFFENBERGER [M'94, SM'01] (feffenberger@huawei.com) received his Ph.D. degree from the University of Central Florida in 1995. He was a staff scientist at Bellcore where he analyzed all types of access network technologies. In 2000 he moved to Quantum Bridge, where he led the development and standardization of advanced optical access systems based on B-PON and G-PON technologies. In 2006, he became Director of FTTx in the advanced technology department of Huawei Technologies. In 2008, he became the chairman of ITU-T Q2/15.

HIROAKI MUKAI received his B.E. and M.S. degrees in electrical and electronic technology from Chiba University, Japan, in 1988 and 1990, respectively. He joined Mitsubishi Electric Corporation, Japan, in 1990. From 1990 to 2008 he was engaged in research and development of optical communication system. Particularly since 1998, he has been engaged in development of PON systems.

JUN-ICHI KANI (kani.junichi@lab.ntt.co.jp) received his B.E., M.E., and Ph.D. degrees from Waseda University, Tokyo, Japan, in 1994, 1996, and 2005, respectively. In 1996 he joined the NTT Optical Network Systems Laboratories, where he was engaged in research on optical multiplexing and transmission technologies. Since 2003 he has been with the NTT Access Network Service Systems Laboratories, where he is engaged in research and development of optical communication systems for access and metro applications. He has been participating in ITU-T and the FSAN initiative since 2003.

MICHAEL RASZTOVITS-WIECH received his Ph.D. degree from Vienna University of Technology in 1996. After three years research in optical intersatellite communications, he continued research in high-speed long-haul optical glass-fiber communications. In 1999 he joined Siemens where he was engaged in product development of optical wavelength division multiplex systems for ultra-long-haul and regional/metro domains. Since 2005 he has been engaged in the development of next generation long reach 10G-PONs. In this field he also contributed to FSAN and ITU-T. Since 2008 he works for Magna Electronics in the field of automotive electrics and electronics.