INVITED PAPER *Special Section on Next Generation Broadband Access Technologies*

Standardization Activities on Broadband Access Systems

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SUMMARY This paper describes international standardization activities on B-PON, GE-PON, and G-PON. This paper explains their distinctive technologies, and compares them from the technical view. This paper also mentions future PON standards which are discussed in some standardization bodies.
key words: *PON, B-PON, GE-PON, G-PON, ITU-T, FSAN, IEEE802.3*

1. Introduction

In Japan, FTTH users will soon overtake ADSL users [1], [2]. This means that the main technology of broadband access systems has moved from metallic systems such as ADSL to optical systems. PON (Passive Optical Network) is the most popular technology for optical broadband access systems because PON can provide optical access services at low cost by sharing transmission equipment [3]. However, PON is more complex than Point to Point optical systems, which connect users to the central office directly. For this reason, PON standardization is important if we are to reduce PON costs. This paper describes the standardization activities on PON and future trends.

2. General Remarks

2.1 Terms of PON

Figure 1 shows a schematic of PON configuration.

A PON consists of one OLT (Optical Line Termination) at the operator's central office and multiple ONU (Optical Network Units) near user houses or multiple ONTs (Optical Network Terminations) in users' houses. ONU is connected to NT (Network Terminal) by DSL (Digital Subscriber Line). ONU refers to both ONU and ONT in this paper.

The OLT and multiple ONUs are connected by optical fibers and optical splitters. The unit of optical fibers and optical splitters is called the ODN (Optical Distribution Network). The protocol at ODN classifies the PON's type.

Signals from OLT to ONU are called downstream signals and those from ONU to OLT upstream signals.

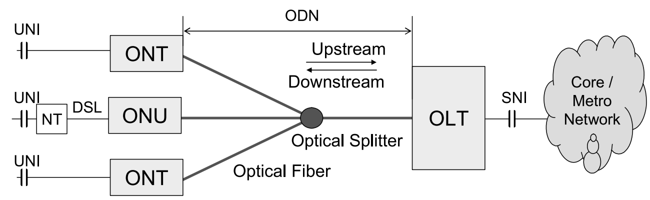

Fig. 1 Schematic of PON configuration.

2.2 STM-PON

STM-PON uses SDH frame at ODN [4]. The upstream signals and the downstream signals are transmitted at the same wavelength, and are multiplexed by TDMA (Time Domain Multiple Access). The physical bit rate is 50 Mbit/s, but the bandwidth of upstream and downstream signals is 10 Mbit/s because a guard time is needed.

STM-PON was studied at the beginning of PON, and NTT performed a field trial in 1994. However, STM-PON was not deployed because its bandwidth is poor given the cost, and it has not been standardized.

2.3 E-PON

An international standard for E-PON (Ethernet PON) was defined at June 2004 by IEEE802.3ah [5]. Before this standard was released, several Japanese vendors deployed their own E-PON systems, which were incompatible with the IEEE E-PON.

IEEE E-PON is called GE-PON (Gigabit Ethernet PON) in Japan (and this paper) for the purpose of distinguishing it from the non-standardized E-PON.

3. Existing PON Standards

3.1 B-PON

B-PON (Broadband PON), the first international PON system standard, was approved in October 1998 as ITU-T Recommendation G.983.1 [6]; it is the basic specification of B-PON. Some additional B-PON Recommendations were approved and revised in ITU-T SG15, and 5 Recommendations, G.983.1 to .5, are now active [7]–[11].

B-PON uses ATM (Asynchronous Transfer Mode) cells at ODN in order to support full communication services using AAL (ATM Adaptation Layer) technologies

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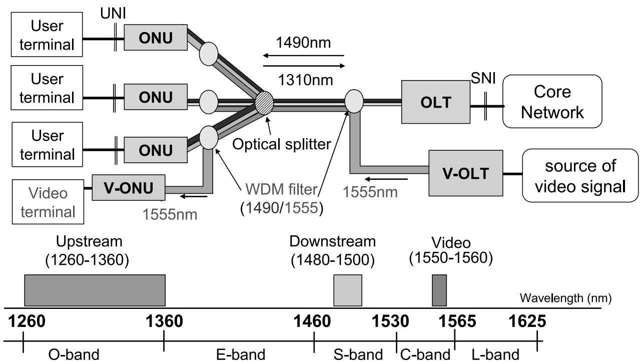

Fig. 2 3-wave multiplexing in B-PON.

Fig. 3 GE-PON MAC frame.

[12]. Typical bit rates are 155 Mbit/s for upstream and 622 Mbit/s for downstream.

B-PON was the patten for subsequent PONs, for example, wavelength allocation in which the O-band was allocated to upstream signals and the S-band was allocated to downstream signals. L-band is reserved for other services such as RF video distribution [13]. Figure 2 shows a typical architecture for multiplexing video signals into a B-PON and the wavelength allocation for the architecture.

3.1.1 Interoperability and CTS

The standardized specifications of B-PON were discussed at FSAN (Full Service Access Networks), which is a carrier-oriented forum for PON systems [14]. FSAN discussed B-PON specifications based on carrier requirements, and sent them to ITU-T SG15 as draft Recommendations.

Multi-vendor interoperability allows carriers to purchase equipments from any vendors. This means that carriers can reduce their investment costs. As for the vendors, multi-carrier common specifications permit the same equipment to be sold to any carriers. Thus the vendors can reduce their development risk, and the efficiency of mass production can be realized.

FSAN also contributes to BPON deployment by establishing interoperability of B-PON equipments and CTS (Common Technical Specifications) for B-PON [15]. The interoperability aims to guarantee multi-vendor interoperability, and CTS is the basis of multi-carrier common specifications.

3.1.2 From B-PON to Gigabit Class PON

B-PON was the first PON system put into commercial services. NTT and Verizon have deployed B-PON systems for their FTTH services with the wavelength allocation shown in Fig. 2 [16], [17]. NTT has moved to GE-PON while Verizon plans to move to G-PON (Gigabit capable PON) for providing FTTH services [18], [19]. This movement from B-PON to another PON is raised by the following problems with B-PON.

- Bandwidth shortage for accommodating GbE or IP-TV in UNI.
- AAL5 accommodates Ethernet packets inefficiently.
- High cost of interface cards because the full specification ATM is not adopted widely
- Reduction in the role of ATM in core systems

These reasons originate from ATM technologies. Newer PONs adopt other frames instead of ATM cells. IEEE aims to reduce the cost of early deployment by setting the use of Ether frame in developing GE-PON. ITU-T aims to accommodate full services by using generic frames in G-PON.

3.2 GE-PON

GE-PON was standardized in June 2004 as the 1000BASE-PX family of IEEE802.3ah which defines gigabit class Ethernet interfaces for access networks including optical Point to Point systems and DSL [5]. GE-PON has been introduced for more than 5 million users in Japan, and is one of the major broadband access systems providing FTTH services in the world.

GE-PON uses Ethernet frames at ODN. GE-PON frame is the same as GbE (Gigabit Ethernet) frame except for the first 8 bytes. GE-PON uses LLID (Logical Link ID) that distinguishes ONU logically instead of the pre-amble used by GbE (see Fig. 3) because the pre-amble is not necessary for GE-PON. Physical bit rate and effective bandwidth are the same as GbE, that is 1.25 Gbit/s physical bit rate and 1 Gbit/s bandwidth after 8B10B decoding. The wavelength allocation is the same as that shown in Fig. 2 for B-PON.

3.2.1 Physical Layer of GE-PON

Figure 4 shows the layer architecture of GE-PON. Physical layer consists of PMD (Physical Medium Dependent) sub-layer, PMA (Physical Media Attachment) sub-layer and PCS (Physical Coding Sub-layer). MDI (Medium Dependent Interface) is used exclusively by GE-PON, and connects PMD and optical fiber. GMII (Giga Medium Independent Interface) is common used in IEEE802.3ah.

PMD sub-layer is newly defined for GE-PON, and defines optical device specifications such as optical power and wavelength. PMA sub-layer defines synchronization of bit and frame. PCS defines 8B10B coding and FEC. PMA sub-layer and PCS are expanded from GbE specifications.

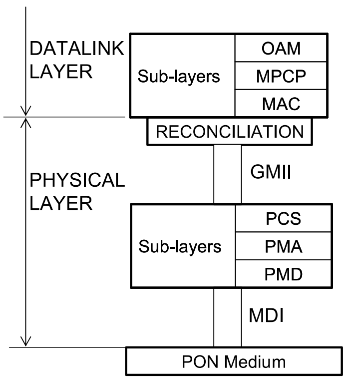

Fig. 4 Layer architecture of GE-PON.

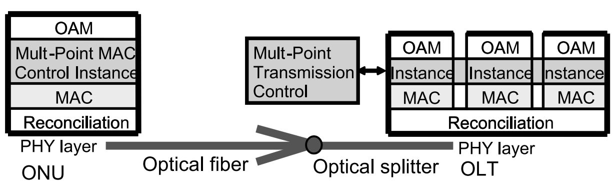

Fig. 5 Data link layer of GE-PON.

3.2.2 Data Link Layer of GE-PON

MAC (Media Access Control) sub-layer and OAM (operation, administration, and maintenance) sub-layer are the same as the MAC layer and OAM layer of GbE. However, MPMC (Multi-Point MAC Control) sub-layer is newly defined for GE-PON, and realizes point to multi-point transmission on GE-PON.

Details of the data link layer of GE-PON are shown in Fig. 5. MPMC sub-layer consists of MPTC (Multi-Point Transmission Control) in OLT and Instance (Multi-Point MAC Control Instance) in OLT and ONU. Each Instance is related to a particular LLID, and blocks out GE-PON frames except for the related LLID. OLT constructs MAC, Instance and OAM for every LLID independently, and ONU constructs one set of MAC, Instance and OAM for each LLID. When MPTC selects an active Instance for each GE-PON frame for the downstream signal, GE-PON establishes the downstream signal whose LLID is related to the Instance. As for the upstream signal, one Instance in OLT passes the signal according to an LLID which is related to an Instance in the source ONU. Thus GE-PON can appear to be a bundle of point to point systems.

3.2.3 Scope of GE-PON Standard

The standardized specifications of GE-PON only cover the physical layer and a portion of the data link layer. Logical link control and system control are beyond the standard, but are necessary for building network systems and ensuring interoperability. When a carrier designs its GE-PON system, it must select standardized specifications or make original specifications to offset the missing details according to its network requirements.

The missing specifications make it easier to provide original services. For example, a carrier can reduce introduction cost by optimizing the GE-PON system for its network, and may adopt patented technologies for control functions such as bandwidth control and authentication. The functions of carrier grade Ethernet, which are beyond the scope of GE-PON, can help in accommodating full services such as leased line services on SDH.

The disadvantages of the missing specifications are that carriers are required to guarantee multi-vendor interoperability by themselves, and vendors can not expect a common specification set. The lack of multi-vendor interoperability and common specification set is a major factor preventing the world-wide deployment of GE-PON.

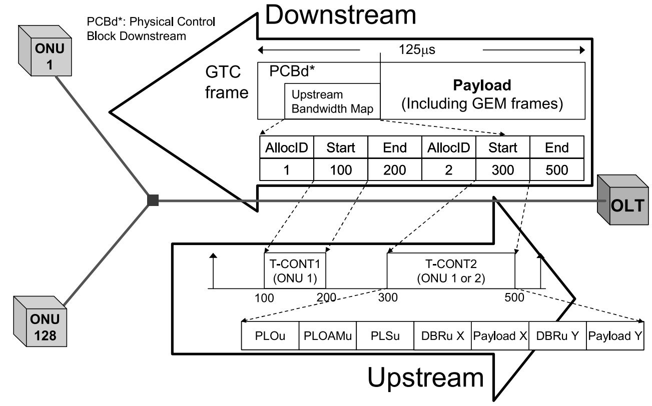

Fig. 6 GTC frame of G-PON.

3.3 G-PON

G-PON was standardized as ITU-T Recommendation G.984 series in ITU-T SG15, and 5 Recommendations are active [20]–[24]. The first Recommendations of G-PON were approved in March 2003 as service requirements G.984.1 and physical layer specifications G.984.2. The full set of G-PON specifications was completed in December 2004 when TC (Transmission Convergence) layer specification G.984.3 was approved. G.984 series were added and revised after 2004, and are being modified.

G-PON uses original dual PON frames: GTC (G-PON Transmission Convergence) frame and GEM (G-PON Encapsulation Method) frame. Details of the frames are described later in this paper. Typical bit rates are 1.24 Gbit/s, upstream, and 2.5 Gbit/s, downstream. The wavelength allocation is basically the same as for the B-PON shown in Fig. 2. A narrower upstream wavelength was defined as G.984.5 in September 2007, see Fig. 11.

3.3.1 GTC Frame

Figure 6 is a schematic of GTC frame. GTC frame consists of header and payload, and multiple GEM frames fill the payload.

PLI	Port ID	PTI	HEC	Fragment Payload
12 -Bit	12 -Bit	3-Bit	13-Bit	L Bytes

Fig. 7 GEM frame of G-PON.

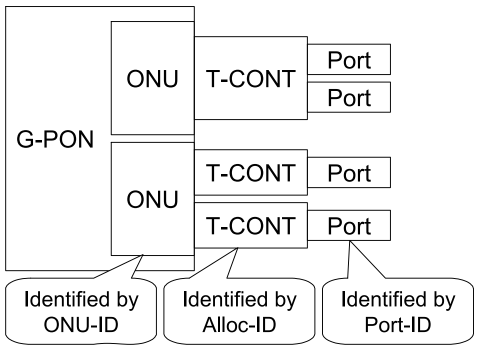

Fig. 8 Identifications numbers of G-PON.

Upstream and downstream GTC frames are different. The downstream GTC frame has fixed length of 125 μs which is synchronized to the base clock of the carrier's network. The header of the downstream GTC frame includes upstream bandwidth map which assigns the bandwidth of upstream signals in the unit of T-CONT (Transmission Container), which is an upstream GTC frame itself. Header length is variable because the length of the map is variable.

In the upstream bandwidth map, Alloc ID (Allocation ID) identifies a target T-CONT, and the succeeding two values show the start and stop slots of the T-CONT. The slots are numbered in the 125 μs time frame which is synchronized to the downstream GTC frame.

3.3.2 GEM Frame

Upstream and downstream GEM frames have the same structure. GEM frame header has fixed length, but the payload has variable length whose value, 'L,' is described in PLI (Payload Length Indicator) in the frame header as shown in Fig. 7. GEM frame is based on the generic frame of G.7041 [25] but is not compatible. Thus, the payload can encapsulate any type of signal without modification.

PLI shows length of payload in bytes. Port ID identifies GEM frame, and shows source address for upstream and destination address for downstream. PTI (Payload Type Indicator) classifies the payload data, that is, the first bit shows OAM or data, the second bit shows start of the data or not, and the third bit shows end of the data or not. HEC (Header Error Correction) is used for error correction.

3.3.3 Signal Multiplexing

G-PON has three identification numbers, see Fig. 8, for distinguishing ONU, QoS, and services.

ONU-ID identifies ONU connected to an OLT. Alloc-ID identifies T-CONT for managing bandwidth and QoS of upstream signals. Port-ID identifies Port for distinguishing service type.

For an example of POTS (Plain Old Telephone Service), Alloc ID assigns upstream GTC frames with the first priority when the QoS of POTS is the highest, and Port ID shows the GEM frames holding the POTS data that the T-CONT carries.

If an ONU has two POTS ports, two Port-IDs are assigned to a T-CONT. If an ONU supports POTS and Internet service, a different T-CONT is assigned to each service because the services have different QoS.

3.3.4 CTS and Interoperability

FSAN is discussing CTS and the interoperability of G-PON. CTS was completed in February 2006 [26], and interoperability testing is ongoing in cooperation with ITU-T and ETSI.

The interoperability testing examines connections between OLT and the ONUs of multiple vendors. Results and demonstrations were shown at ITU Telecom World 2006 [27] and NXTcomm 2007. The connections considered were/are limited with a few particular OLT — ONU combinations that constitute 40% of all combinations possible.

G-PON interoperability is more difficult than B-PON interoperability because G-PON adopts new and complicated frames and includes many options. G-PON standards should be modified based on the results of the interoperability testing, and are expected to eliminate useless options.

It is remarkable that some vendors readily offer just the ONU with the expectation of universal interoperability with OLT. The existence of ONU-only vendors suggests the feasibility of a world wide market.

3.4 Comparison of Existing PONs

Figure 9 shows the trend in worldwide PON deployment. GE-PON is deployed in many Asian countries due its adoption by Japan. Some USA and European companies plan to introduce G-PON [19], [28], [29], but no major carrier has done so yet. This is because DSL is a major broadband ac-

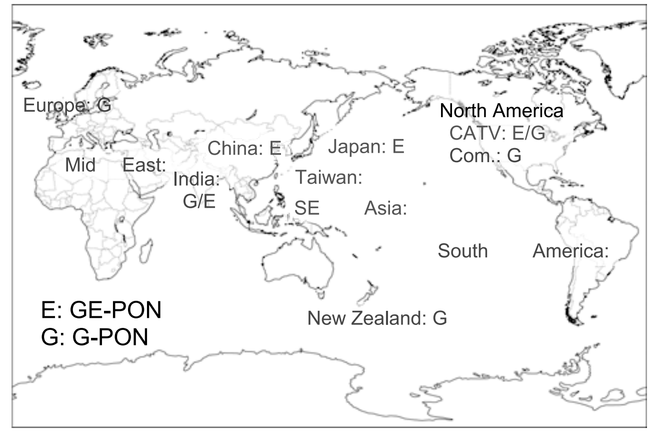

Fig. 9 Trend in worldwide PON deployment.

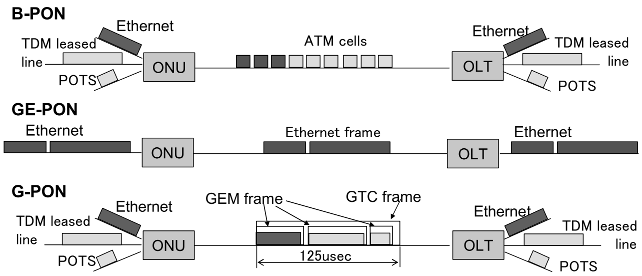

Fig. 10 Frame structures of B/GE/G-PON.

cess technology in USA and European countries, and they are waiting for stabilization of G-PON standards and realization of G-PON equipment interoperability.

Figure 10 shows frame schematics of the existing PON. B-PON divides the signals into ATM cells. GE-PON transmits Ethernet data by Ethernet frames. G-PON packs each signal into a GEM frame of variable length. GTC frames include GEM frames and is synchronized to a 8 kHz clock.

UNI tends to support only Ethernet due to the rapid progress of carrier-grade Ethernet technologies. POTS can be transposed to VoIP (Voice over IP), and TDM leased line services can be provided by Ethernet via circuit emulation technologies. Accordingly, most G-PON equipment offers only Ethernet-based UNI, and G-PON transmits only Ethernet signals by the more complicated frames than GE-PON.

IPTV service will take off soon. If the IPTV services are provided in broadcasting 100 channels of HDTV (High Density TV), the required bandwidth is at least 1 Gbit/s. G-PON can add IPTV signal broadcasts to the 1 Gbit/s data services easily because its downstream bandwidth is 2.5 Gbit/s. GE-PON has insufficient bandwidth for the broadcast IPTV services, but can provide IPTV services by using other technologies such as multicasting.

4. Future PON Standards

4.1 10GE-PON

In March 2006, a discussion to add new 10 Gbit/s-interface specifications to GE-PON was started in IEEE. The first stage of the meeting discussed whether the time was appropriate to start 10 Gbit/s access or not. Some people were concerned that it was premature to introduce 10 Gbit/s-class access from technical and service viewpoints. However, the majority opinion supported starting work on the new standard. Technical discussions on 10GE-PON (10 Gbit/s E-PON) are underway in the IEEE 802.3av task force. Standardization should be completed by September 2009.

Figure 4 also shows the layer architecture of 10GE-PON. The 802.3av task force is focusing its discussion on adding a 10 Gbit/s physical layer specification to GE-PON, i.e. data link layer details such as OAM and MPMC sublayers will be basically kept unchanged. The 10 GBASE-R specification can be used for some parts of the physical layer specifications such as PCS and PMA sub-layers. Therefore, PMD specifications are the main discussion topics. The task force is targeting asymmetric type PMDs with 1 Gbit/s upstream and 10 Gbit/s downstream signaling, and symmetric type PMDs with 10 Gbit/s bi-directional signaling.

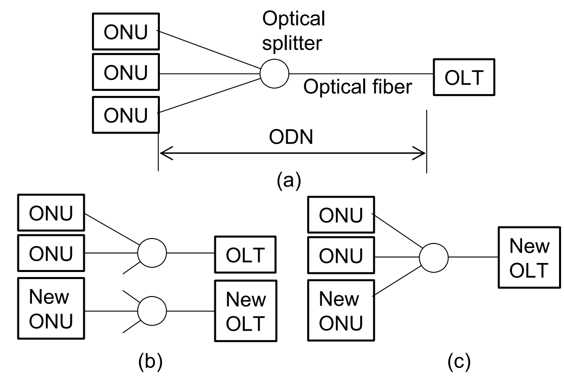

Fig. 11 Schematic view of PON. (a) single system, (b) upgrade without co-existence, (c) upgrade with co-existence.

4.1.1 Features of 10GE-PON

10GE-PON is the next generation of GE-PON. The system will be deployed to replace GE-PON as well as green field installation. For the smooth migration from GE-PON to 10GE-PON, 10GE-PON should co-exist on the same ODN with existing systems, such as GE-PON system and video distribution system [13].

Figure 11(a) shows a typical PON configuration. In the PON, one OLT and one ODN are shared by multiple ONUs, therefore upgrading one user to the new system requires another ODN, new OLT and new ONU, as shown in Fig. 11(b). In this case, a large amount of fibers is necessary for the upgrade.

To realize smooth migration from one PON system to the next generation system, co-existence between the two systems is critical (Fig. 11(c)). Existing standards such as B-PON, G-PON and GE-PON do not support such co-existence functionality, because PON systems were not widely installed at the time these systems were developed. Since PON systems are now widely deployed for commercial use, so co-existence is much more important for next generation access.

The 802.3av task force intends to develop a specification that can support co-existence; note that the development of the co-existence technology itself is beyond the scope of the task force. TDMA is being discussed for upstream direction co-existence with GE-PON, and WDM is being considered for downstream signaling. Figure 12 shows a wavelength allocation draft for 10GE-PON. For the upstream direction, full bandwidth of the 1310 nm band is allocated for GE-PON. Therefore, the task force allocates upstream wavelength in the 1310 nm band on the premise of co-existence technologies with TDMA and multi-rate burst receivers in the OLT. Downstream signaling can adopt a different wavelength from existing systems such as GE-PON,

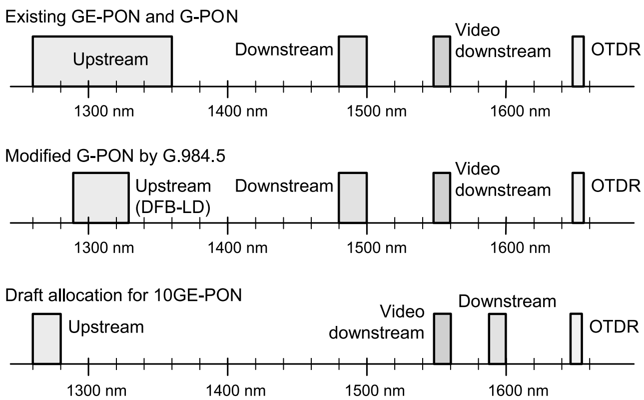

Fig. 12 Draft of wavelength allocation for 10GE-PON.

Table 1 Draft baseline technologies of 10GE-PON.

		PR10	PR20	PR30
Channel insertion loss		20 dB	24 dB	29 dB
Upstream	transmit	DML	DML	Hi-DML
	receive	APD	APD	APN
Downstream	Transmit	Hi-EML	EML and OA	EML
	receive	PIN	PIN	APD

DML: direct modulation LASER
EML: external modulation LASER
OA: optical amplifier

video distribution, and OTDR (Optical Time Domain Reflect meter). Therefore, WDM-based co-existence can be used.

In addition, ITU-T redefined the narrower wavelength range for upstream G-PON as ITU-T Recommendation G.984.5 in September 2007 for future wavelength extension [24]. The upstream wavelength of the original G-PON was specified as the full bandwidth of O-band in G.984.2 [21] the same as GE-PON. The wavelength of 10GE-PON is considered to co-exist with the G-PON of the new upstream band using WDM. Therefore, 10GE-PON specification is consistent with smooth migration from either GE-PON or G-PON.

GE-PON specifications 1000BASE-PX10 and -PX20 support the channel insertion loss values of 20 dB and 24 dB, respectively. However, actual PON systems for commercial use require a larger optical loss budget 28 dB and 30 dB as shown in class B+ and class C, which are defined in G.984.2. Therefore, the 802.3av task force is discussing a new class of optical loss budget to support 29 dB channel insertion loss.

Signaling at 10 Gbit/s with large optical loss budget requires that tough specifications beset for the optical devices. The 802.3av task force spent a long time in a heated argument on whether the receiver device of ONU should be PIN-PD (PIN Photo Diode) or APD (Avalanche Photo Diode). Table 1 has been adopted as a draft of base-line technologies for 10GE-PON. To relax the requirements for the optical components, streaming FEC (Forward Error Correction) is being discussed.

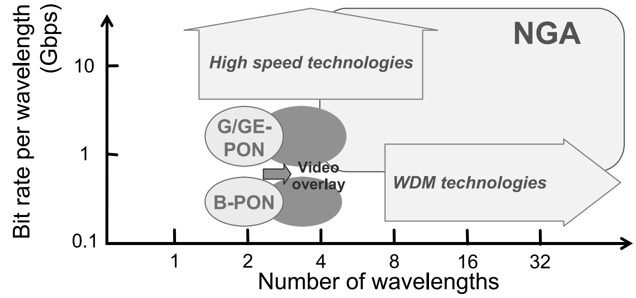

Fig. 13 Technical direction for NGA.

4.1.2 Discussion of 10GE-PON Features

The standardization of "10 Gbit/s PHY for E-PON" is progressing. However, its completion does mean the completion of a full 10GE-PON system. IEEE defines just the interface specification, and much other functionality is needed to realize a commercial system. The lack of common system requirements makes it difficult to achieve interoperable GE-PON devices. Therefore, discussion on not only the interface but also the system is important to achieve the next generation E-PON system. Details of this discussion are described later in this paper.

4.2 NGA

FSAN is discussing Next Generation Access (NGA) based on carriers' requirements for broadband access networks [14]. Most of the requirements have been agreed as follows.

- Maximum utilization of the ODN installed for existing PONs
- Flexible upgradeability to accommodate to various upgrade requirements at various times.
- Capability to provide higher bandwidth/capacity than existing PONs.
- Optimized technology combinations in terms of cost and performance.

FSAN plans to issue a white paper on NGA before early 2009 in order to provide concrete requirements and rough specifications.

4.2.1 Technical Direction

NGA is considering high speed technologies and Wavelength Division Multiplexing (WDM) technologies as its technical direction as shown in Fig. 13. The target of downstream bandwidth is clear, 10 Gbit/s, and the lower upstream bandwidth looks feasible. Thus the upstream bandwidth is one issue for the white paper. WDM technologies can be used to realize the co-existence of NGA and existing PONs. WDM-PON and stacked PON are interesting applications of

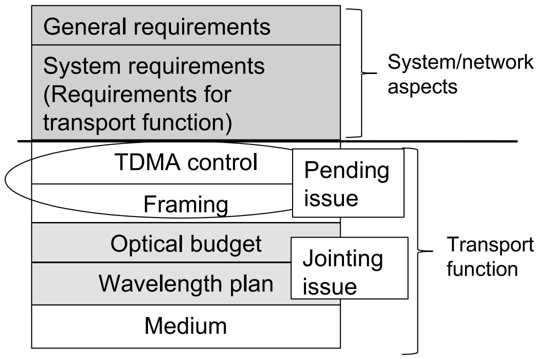

Fig. 14 An example of collaboration with 10GE-PON.

WDM technologies, but a more detailed discussion is necessary to achieve a real solution.

Longer reach and higher splitter ratios are also physical layer requirements for NGA. This issue includes the study of optical amplifiers suitable for PON [29], and is being discussed in G-PON ahead of NGA. CDM (Code Division Multiplexing) technology could be another technical direction given the above requirements [31], but FSAN has not yet reached a conclusion as to the availability of CDM.

4.2.2 Collaboration with 10GE-PON

NGA will use common specifications on physical layer with 10GE-PON because most of both physical layer requirements are the same, such as downstream bandwidth, wavelength plan and optical budget. This is the same situation about G-PON and GE-PON. NGA can also be expected to use the similar specifications on data link layer reflecting with progress of carrier-class Ethernet.

ITU-T and FSAN expect G-PON and NGA to support all of existing services under multi-vendor interoperability. G-PON introduces new frame architecture for supporting full services, but the new frame raise complicated issues on interoperability. Ethernet frame on NGA is one possible solution for achieving interoperability easier.

Figure 14 shows an example that NGA can collaborate with 10GE-POIN. The physical layer specifications of NGA can be common with 10GE-PON. The common specifications on data link layer should be discussed later waiting for the discussion of carrier-class Ethernet technology. System requirements of NGA can be confirmed independently with 10GE-PON because 10GE-PON focuses only on transport functions.

4.2.3 Evolution Scenario

The standardized PON began with B-PON, and has split into GE-PON and G-PON. These existing PONs use the same ODN, but they can't co-exist because they use the same wavelength for up and downstream signal. The competition between them has accelerated standardization activities, but prevented mass production on a worldwide scale. It is very important for the next PON to co-exist with the previous PON from the aspect of maximum utilization of installed ODNs and flexible upgrading.

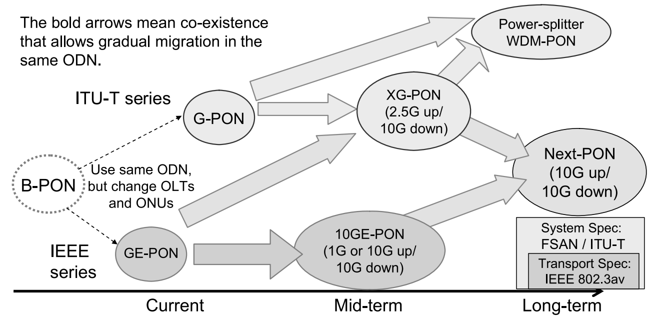

Fig. 15 An example of evolution scenario.

Figure 15 shows an example of an evolution scenario in which the 10 Gbit/s class PON will be unified to realize the mass effect. WDM-PON will construct a different series because ODN might be different from the 10 Gbit/s class PONs. Long reach technologies could be adopted in the background of this scenario.

4.2.4 Other Issues

Reduction of operation expense (OPEX) is a notable issue for reducing total cost. OPEX itself means the cost of maintenance and repair, but the methods for OPEX reduction are also effective for fiber replacement and so on. If the methods are standardized, each carrier could adopt them in the most advantageous manner.

Carriers will be able to provide many types of services as their access network bandwidth becomes broad. These multiple services require service specific transmission parameters on the access network, such as QoS and bandwidth through the home network requirements.

5. Conclusion

PON standardization activities are vigorous and multiple specifications have been released. The next PON is forming as IEEE 10GE-PON, and research into system requirements for the next generation PON has begun in FSAN as NGA. 10GE-PON and NGA are expected to collaborate with each other to ensure the effective advancement of optical broadband access systems.

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