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Past, Present and Future of Passive Optical Network

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ABSTRACT

Demand for faster and cheaper access network has been rising due to the rapid growth of Internet with new generation of services and applications. Optical fiber has been envisioned for delivering broadband services for more than 30 years and becomes almost essential recently. To address the present and future bandwidth demand, broadband fiber access technologies such as Passive Optical Networks (PONs) are a potential solution. Mostly, Time Division Multiplexing (TDM) based PON is deployed all over the world. Researchers have been investigating some next-generation PON systems to mitigate the future bandwidth demand. In this paper, we review the history of PONs, examine their current status, and finally investigate the probable future PONs. We also review the key enabling features for future PONs and smooth migration process from the current status to the future technologies.

Keywords: *Passive Optical Network (PON), Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM), Code Division Multiplexing (CDM), FTTx*

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INTRODUCTION

In the recent years, multimedia services such as Video On Demand (VOD), Content On Demand (COD), video/tele-conferencing, High-Definition Television (HDTV), interactive games, and Voice Over Internet Protocol (VOIP), Internet users will demand more than 100 Mb/s of guaranteed bandwidth per user by the year of 2012 [1,2]. Many service providers are planning to provide networks capable of 100 Mb/s or higher, per customer. There is a strong competition among the technologies such as coaxial cable, wireless, Digital Subscriber Loop (DSL), and FTTx (Fiber to the x, where x stands for node, curb, building, home, and premise) to provide broadband access services to the end users. Due to the physical constraints of the copper wire and wireless technologies, deployment of FTTx based access networks are the ultimate goal of the network service providers. However, in order to provide cost-effective solution, RF over Glass (RFoG) is also considered as a promising technology for hybrid fiber/coax (HFC) and FTTP bridging architecture [3]. According to the FTTH Council, there are 50 million FTTH/B connections worldwide by May, 2010. More than 39 million FTTH/B connections are accounted by the Asian region. At the end of 2013, the number of FTTH/B subscribers is expected to be ~130 million. Worldwide FTTH household penetration is represented in [4]. The worldwide forecast of the wire

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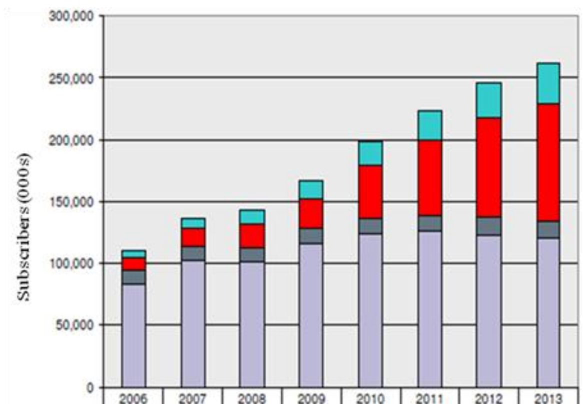
line broadband subscribers in terms of deployment technologies is represented in Figure 1 [4].

Depending on the use of passive or active devices, an FTTx network can be classified as follows: Passive Optical Network (PON) and Active Optical Network (AON). Further, from topological point of view FTTx can be



	2006	2007	2008	2009	2010	2011	2012	2013
FTTH	5,348	8,001	11,403	15,161	19,176	23,567	28,332	32,454
FTTB	10,618	14,492	18,645	23,816	42,872	60,921	80,851	94,959
Cable modem	10,872	11,665	12,157	12,540	12,925	13,337	13,769	14,230
DSL	83,611	102,037	100,962	116,063	123,611	125,514	122,877	119,683

Fig. 1 Cumulative Wire line Broadband Subscribers Forecast (February 2010) [4].

categorized as follows: Point-to-Point (P2P) and Point-to-Multi-Point (P2MP) systems. In a P2P topology, a separate fiber runs from an Optical Line Terminal (OLT) in the Central Office (CO) to an Optical Network Unit (ONU) at some node point for each user. This model is suitable for enterprise type networks. However, this kind of networks is difficult to assemble in a large scale due to the huge costs of deployment and maintenance. On the counterpart, in a P2MP topology the feeder fiber runs from the OLT of the CO up to a splitting point in the path. From this point, shorter fibers extend to several ONUs at the end points. The P2MP architectures have gained wide attention from the network service providers partly due to the 20-35% capital expense reductions achieved by fiber and OLT sharing [5]. Figure 2 shows the simple architecture of the P2MP based AON and PON systems. In order to distribute the signals, AONs require some active equipment (electrically powered equipment) such as Ethernet switch, router, or multiplexer at the splitting point. On the counter part, PONs requires passive equipment such as optical splitters or Arrayed Waveguide Grating (AWG) at the splitting point.

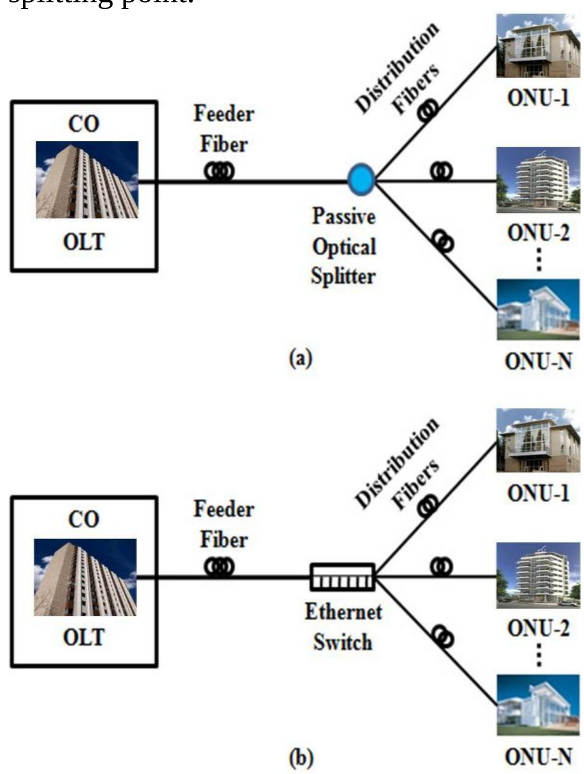


Fig. 2 Architecture of P2MP Based Optical Networks. (a) Time Division Multiplexed Passive Optical Network (TDM-PON); (b) Active Optical Network (AON).

In the rest of the paper, we focus on PONs as an essential FTTx architecture. The progress in this sector, different PON standards, and their deployment trends has been discussed. It is noteworthy to mention here that the industry has selected TDM-PONs for current PONs' deployments almost everywhere. To satisfy future bandwidth demands, probable next generation PON systems are under assessment. In this paper, at first we review the current generations PONs. We also investigate the probable next generation PON systems. Furthermore, the key enabling components and technologies for the next generation PON systems are analyzed. Above all, we will discuss in brief about the possibility of smooth up-gradation process of the present PON systems to the future generation PON systems in an economical manner.

OVERVIEW OF PASSIVE OPTICAL NETWORKS

A PON is a point-to-multipoint (P2MP) FTTx network architecture made up of optical fiber cabling, passive splitters or AWG, and optical couplers that is used to distribute optical signals through a tree type network to end users' connectors that terminate each fiber segment. Researchers realized that, it would be possible to achieve the delivery of optical signals using the cost sharing FTTx network passively. A PON has some important advantages over other networks:

- It eliminates the need for active optoelectronic and electronic devices and reduces the power consumption.
- P2MP deployment requires less fiber layout to cover a certain area than its P2P counterpart using individual fibers to each customer, which topology reduces the overall cost.
- Since PON is able to provide services to many users using a single OLT in the CO, the overall cost are reduced.
- PON eliminates the noise from the active components and removes electromagnetic interference (EMI).

We categorize PONs into current generation PONs and next generation PONs. Current generation PONs include the TDM-PONs such as Asynchronous Mode PON (A-PON), Broadband PON (B-PON), Gigabit capable PON (G-PON), and Ethernet PON (E-PON). The next generation of PONs is sub-categorized into short-term and long-term future generation PONs: 10 G-EPON and XG-PON are considered as short-term future generation PONs, while WDM-PON and hybrid WDM/TDM-PONs are considered as long-term future generation PONs.

PON was first introduced in 1980s.The search for a TDMA system over a PON was proposed in 1987 by researchers at BT Laboratories and the first TDMA-based system was developed in 1989 [1]. One of the most significant events in the history of PON networks was the founding of Full Service Access Network (FSAN) group in 1995 [6]. The initial PON specifications defined by FSAN committee used ATM (Asynchronous Transfer Mode) as their layer 2 signaling protocol. This standard was adopted by ITU-T (ITU-T G.983.1) and referred to as ATM PON (A-PON). Nippon Telegraph and Telephone (NTT) first deployed A-PON in Japan as a solution for broadband data access services.

In order to deliver a full set of telecommunications services, FSAN has also produced the initial recommendations for Broadband-PON (B-PON) since 1996, which were adopted by ITU-T as ITU-T G.983.x series since 1998. B-PON has been deployed in North America in large scale until 2007. It is deployed in Asia also. Around 5% of the total PONs was B-PON in 2009 [7].

In 2001, the IEEE 802.3 working group initiated a task force, called 802.3ah to draft a standard to address Ethernet in the First Mile (EFM). The main objective was to standardize the transport of Ethernet frames (1000Base-x) over PONs. The result was a simple system known as Ethernet-PON (E-PON). Currently there are wide E-PON deployments (around 55% by the end of 2009), especially in China, Korea, Japan, and south-east Asia.

In 2001, the FSAN start a new effort for standardizing networks operating at bit rates of above 1 Gb/s. The goal of FSAN was to find the most favorable and efficient solution to provide supports for multiple services, operation, administration, maintenance, provisioning functionality, and scalability. In 2003, the FSAN proposed the first recommendation for Gigabit capable PON (G-PON), which is adopted by ITU-T G.984.x series. Around 21% of the total PONs was G-PON at the end of 2009 [7], those are mainly deployed in North America and Europe. A comparative analysis of the number of connections of different PONs is shown in Figure 3 [7].

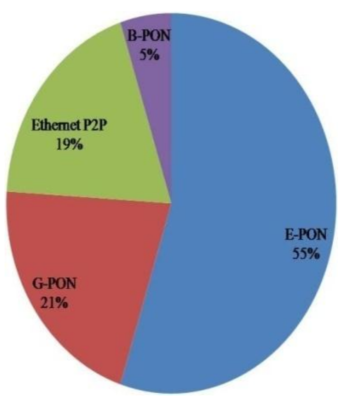


Fig. 3 Worldwide Market Share of Different Pon Systems at the End of 2009 [7].

Although G-PON still lagging behind E-PON worldwide in terms of number of installed connections, G-PON is expected to dominate in the near future as some of the players of this industry are expected to increase their use of G-PON. Worldwide equipment revenue forecast for E-PON and G-PON is shown in Figure 4 [8].

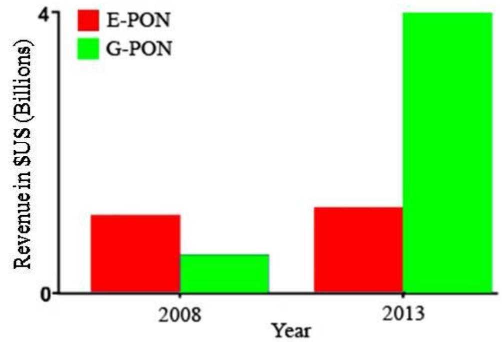


Fig. 4 Worldwide Equipment Revenue Forecast of E-PON and G-PON in March 2009 [8].

Due to the increasing demand of bandwidth, the FSAN/ITU-T and IEEE have begun to consider TDM-PONs that can operate in 10 Gb/s. WDM-PON and CDM-PON and their combination such as hybrid WDM/TDM-PON and DWDM-CDM-PONs are also widely discussed by researchers, although they are not standardized yet. In WDM PON, dedicated wavelengths are allocated for each individual user, which PON structure will be discussed in details in the next section. On the contrary, CDM technologies have been widely used and deployed in wireless communication and have studied in optical access networks as well. It provides many unique features, such as ultra long reach and bidirectional transmission using the same wavelength with single fiber, and higher symmetric bandwidth. Different users/codes can carry different interactive services, such as data, voice, or video. However, CDM based PONs suffer from some problems such as inter-channel interference and management of higher signal rate by the physical components, which rate is much higher than the user's data rate. CDM-PONs as well as DWDM-CDM-PONs are still limited to only research based works [9-11].

In this paper, we mainly focused on TDM-PONs and WDM-PONs. The hybrid TDM/WDM-PONs will be discussed also for smooth migration from TDM-PONs to WDM-PONs.

CURRENT GENERATION PONS

Currently, TDM-PONs are mostly deployed all over the world. Figure 1(a) shows a typical TDM-PON architecture. A-PON, B-PON, E-PON and G-PON can be considered as the current generation TDM-PONs. These PON systems are discussed briefly in this section.

Asynchronous Transfer Mode PON (A-PON)

A-PON systems are based upon ATM as the bearer protocol. The network components supporting A-PON consists of OLT, ONUs and passive optical splitters as shown in Figure 1(a). One fiber can be passively split up to maximum 32 branches to support 32 ONUs.

Downstream transmission is a continuous stream of timeslots, each timeslot containing 53 octets of an ATM cell or a Physical Layer OAM (PLOAM) cell at a bit rate of 155.52 Mb/s. Every 28 time slots, a PLOAM is inserted. In the upstream direction, the frame contains 53 time slots of 56 bytes. Upstream transmission is in the form of bursts of ATM cells which adopts TDMA protocol to distinguish each ONU. In each upstream slot, a 3 byte overhead header and 53 byte ATM cell can be transmitted by each ONU. The frame structure of 155.52/155.52 Mb/s system (A-PON) is shown in Figure 5 [12].
Each ATM cell has a 28-bit addressing field associated with it (among 53 byte cell), called a Virtual Path Identifier/Virtual Channel Identifier (VPI/VCI). The OLT first send a message to the ONU with certain VPI/VCI values. The ONU will filter the incoming cells and recover only those that

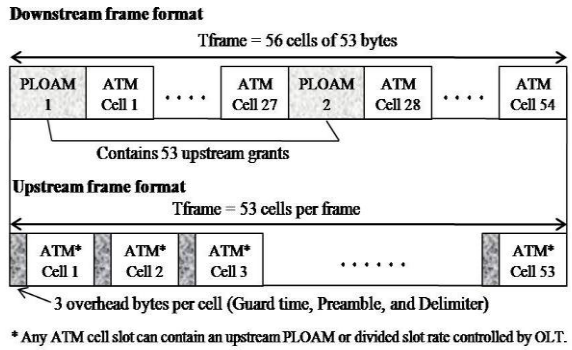


Fig. 5 Downstream and Upstream Frame Structure of A-PON [12].

are addressed to it. The OLT assigns an optimal time slot for each ONU and the ONU will adapt its service interface to ATM and send it to the OLT by using TDMA protocol in the assigned time slot. The value in the grant field of the downstream PLOAM cell indicates the assigned time slot for an ONU.

Broadband PON (B-PON)

In order to fulfill the requirement of upgrading A-PON by the service providers, B-PON is evolved although some researchers consider A-PON and B-PON as same. The B-PON architecture is almost similar to A-PON. The main difference is the 622 Mb/s downstream, and 155 Mb/S or 622 Mb/s aggregate upstream data rates. It also provides maximum 32 split with a maximum reach of 20 km. The frame structure of 622/622 Mb/s B-PON is shown in Figure 6 [13].

The ranging of A-PON/B-PON is operated by the OLT. The OLT sends a ranging grant and stops the traffic in the network and waits for the ONUs to send their ranging

PLOAMs. During ranging procedure, the OLT sends a PON-ID to each active ONU. These IDs are used to send data to each ONU individually. After initialization, each active ONU can transmit data according to the given grants. Similar to A-PON, the ONU of B-PON needs to synchronize with the downstream frame depending on the

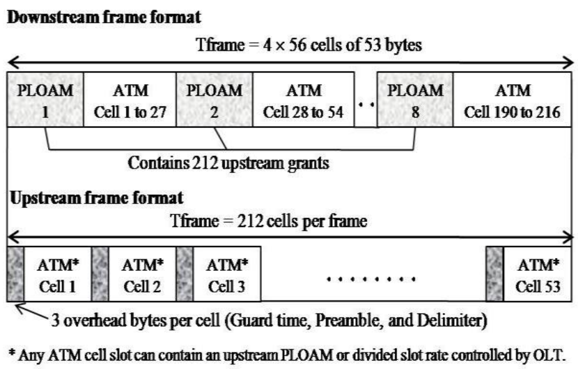


Fig. 6 Downstream and Upstream Frame Structure of 622/622 Mb/s B-PON [13].

frame bit in the downstream PLOAM cells in order to access the upstream link [14]. The wavelength allocation of A-PON and B-PON are shown in Figure 7 [5].

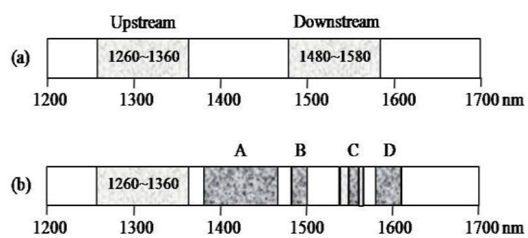


Fig. 7 Wavelength allocation for A-PON and B-PON. (a) Original spectrum allocation for A-PON; (b) Subsequent allocation for B-PON providing wavelengths for enhancements and other future uses [5].

The new wavelength allocation was made to improve B-PON's support for broadcasting and multicasting of a wide variety of high speed digital services. In the new wavelength allocation scheme, the downstream wavelength window is divided into the normal downstream band (1480–1500 nm, known as B-band) and enhancement band. The band B is used for regular ATM downstream transmission. The enhancement band (band C) can be allocated for video distribution option (1550-1560 nm) or other downstream digital services (1539-1565 nm) including Dense Wavelength Division Multiplexed (DWDM) services. Band A (~1380-1460 plus guard bands) and band D (1570-1610 nm) are reserved for future use.

Ethernet PON (E-PON)

We already know that E-PON concept was standardized by IEEE (IEEE 802.3ah), which was published in September 2004. The E-PON concentrates on defining Ethernet based P2MP PON network. It specifies a symmetrical upstream and downstream line rate of 1 Gb/s. The maximum possible number of ONUs per OLT is 32. The E-PON exploits TDM technique for downstream and TDMA technique for the upstream communication. E-PON operates at the wavelength of 1490 nm to the downstream and 1310 nm to the upstream direction. This leaves the 1550 nm wavelength window open for additional services. The E-PON Physical Media Dependent (PMD) layer defines two alternative optical ranges: 10 km for short reach and 20 km for long reach.

The frame structure of E-PON is based on the standard Ethernet frame. The difference between these two kinds of frame is found in the preamble field, which has been modified to carry 2-byte Logical Link Identification (LLID) field, Start of Packet Delimiter (SPD) that is transmitted as 0×D5, and the CRC8 field, which is calculated over the first bit of the SPD through the last bit of the LLID. The first bit of the LLID field indicates the mode (P2P or broadcast mode) and the remaining 15 bits identify the ONUs. The frame structure of E-PON is shown in Figure 8 [14].

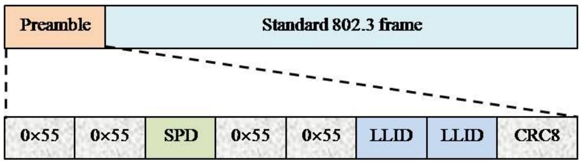


Fig. 8 Frame Structure of E-PON [14].

In the upstream direction, Multi-Point Control Protocol (MPCP) handles the traffic co-ordination. The MPCP functions are enabled with an extension in the MAC control sub-layer, called the multipoint MAC control sub-layer required for P2MP operations. The OLT and ONUs use 32-bit counter for calculating local timestamps. The counters are incremented every 16 ns. During the ranging period, the OLT inserts a timestamp in the ranging message and the receiving ONU resets its counter according to the timestamp. After this, the ONU generates a ranging message and sends to OLT, which includes the ONU's current timestamp. The OLT calculates the Round-Trip time to determine when to assign grants to this ONU. The OLT assigns timeslots for each registered ONU, which can send burst data during this time slot. In downstream direction, ONUs will accept those frames for further processing that carry their LLID tag [14].

Gigabit capable PON (G-PON)

The aim of G-PON was to improve the B-PON system by re-evaluating the supporting services, security policy, and optical fiber infrastructure. It specifies a line rate of 2.4 Gb/s downstream and 1.2 Gb/s for upstream with a maximum physical reach of 20 km. The G-PON supports split ratio up to 64. The wavelength allocation for G-PON is 1480-1500 nm for downstream (considering video overlay) and 1260-1360 nm for upstream. The downstream and upstream frame format of G-PON is shown in Figure 9 [14].

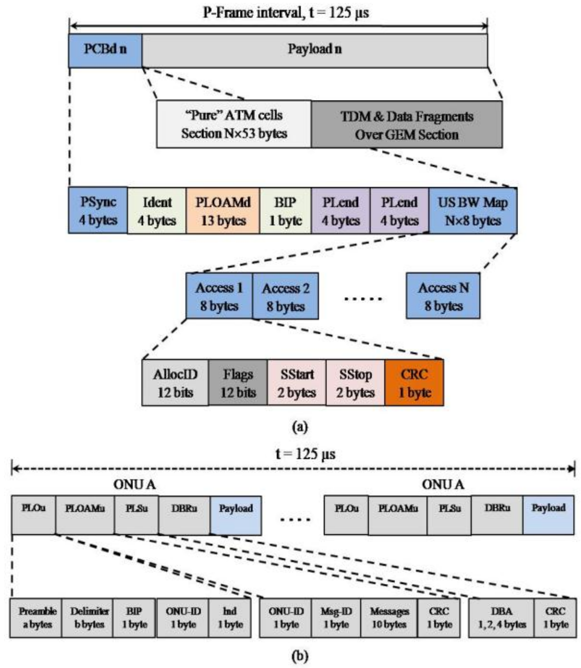


Fig. 9 Frame structures and overheads of G-PON. (a) Downstream frame structure; (b) Upstream frame structure [14].

For downstream communication, G-PON uses similar frame structure as the Synchronous Digital Hierarchy (SDH) concept. In every 125 µs, one frame is transmitted to upstream and downstream direction, which allows the clock distribution and synchronous data transfer. The downstream frames can carry six types of overheads: PSync, Ident, PLOAMd, BIP, PLend, and BW Map.

The frame size depends on the transmission speed (19440 bytes for 1.2 Gb/s and 38880 bytes for 2.5 Gb/s). The downstream frame is scrambled and Non-Return to Zero (NRZ) line coded before transmission. For upstream communication, several ONUs can send data during one frame period depending on the timeslot allocations done by the OLT. The upstream frames can carry four types of overhead: Physical Layer Overhead (PLOu), Physical Layer OAM overheads (PLOAMu), Power Levelling Sequence upstream (PLSu) and Dynamic Bandwidth Report upstream (DBRu) as shown in Figure 8 (b). The ranging procedure of G-PON is similar to that of B-PON. An ONU has 8 states, each of which serves some definite function. After passing the preliminary, standby, power range setup, and ONU-ID assigning the ranging states, the normal operation state is reached. There are some states those are assigned for specified network failure conditions.

For upstream traffic, the G-PON performs media access control. The downstream frames, from the OLT, inform the ONUs during which timeslot they can transmit and also carry the synchronization information to the ONUs to avoid overlapping. There are two type of switching in G-PON for protection schemes: automatic switching and forced switching, which feature ensures the reliability of the network [14].

NEXT GENERATION PONS

Although the current generation PONs such as G-PON and E-PON is sufficient to meet the present demands for broadband access, a few next generation PON systems have been proposed by both academia and industry. In order to give a comprehensible thought, we categorize the next generation (NG) PONs as short-term future generation PONs and long-term future generation PONs. In the short-term systems, the main focus is on the bandwidth with the existing PON infrastructure; however, long-term systems are focused on some new architecture and technologies to support high capacity, realize cost effectiveness, or ease network scalability.

Short-term Future Generation PONs

The FSAN/ITU as well as IEEE has begun to work with some TDM based systems with speeds of 10 Gb/s that can operate with the existing PON infrastructure.

In 2006, the IEEE 802.3av task force was established to develop 10 G-EPON systems, which was standardized in September 2009. The targeted systems include a symmetric system 10 Gb/s downstream and upstream (10G/10G-EPON) and an asymmetrical system with 10 Gb/s downstream and 1 Gb/s upstream (10G/1G-EPON). The 10G/1G system may be considered as the intermediary system for migrating to the 10 Gb/s system from the existing E-PON system. The symmetric 10 G-EPON is the ultimate target for short-term solutions from IEEE. In order to enable the simultaneous operation of 1Gb/s and 10 Gb/s E-PON systems using the same plant, 1480-1500 nm band is used for 1Gb/s and 1575-1580 nm band is used for 10 Gb/s transmission in the downstream direction. In the upstream direction, 1260-1360 nm band is used for 1Gb/s and 1260-1280 nm band is used for 10 Gb/s transmission, which system allows both upstream channels to share the same spectrum. However, the 1 Gb/s and 10 Gb/s are separated in time domain. The 10 G-EPON adopts a stream-based Forward Error Correction (FEC) technique based on Reed Solomon (255,223), which mechanism is mandatory for all the channels operating at 10 Gb/s [15].

Some researchers are trying to improve and analysis the performance of 10 Gb/s upstream to make it practical [16,17]. However, still 10 Gb/s symmetric system is technically and economically challenging and may take several years to become practical.

The FSAN group, on the other hand, considered 10-gigabit capable passive optical networks (XG-PON) systems and standardized in 2010 (ITU-T G.987.x series). The maximum split ratio of XG-PON is 64 with a maximum reach of 20 km. There are two types of XG-PON based on the upstream line rate: XG-PON1, featuring 2.5 Gb/s upstream and 10 Gb/s downstream; and XG-PON2, featuring 10 Gb/s in both downstream and upstream transmission. The XG-PON1 is the primary focus of FSAN and XG-PON2 will be addressed in a later phase, when the technology becomes more mature. In XG-PON systems, 1575-1580 nm band is used for downstream and 1260-1280 nm band is used for upstream transmission. The enhancement bands are allocated for the coexistence of G-PON (1290-1330 nm band for upstream, 1480-1500 nm band for downstream) and/or video distribution service (1550-1560 nm band), and future use (1360-1480 nm band). The physical layer of XG-PON1 uses scrambled None Return to Zero (NRZ) line coding in the downstream and upstream transmission [18].

The XG-PON2 is the ultimate version of TDMA by FSAN. The need of the coexistence between XG-PON1 and XG-PON2 still needs further study. It is enviable to support a common TC layer for XG-PON1 and XG-PON2 is resulting from G-PON’s TC with the necessary enhancements. Among different solutions of converging XG-PON1 and XG-PON2, one possible solution has been proposed in the Joint ITU-T/IEEE Workshop on Next Generation Optical Access Systems in 2008 [19].

Researchers already implemented the XG-PON1 in co-existence with a commercially deployed G-PON system [20]. Extended reach/split versions of the XG-PONs are also discussed, for allowing the WDM-aware OLT/ONU components to permit multiplexing on the feeder fibers using regenerator or optical amplifiers to reach more than 60 km [21].

Recently both IEEE and ITU-T realized the importance of reducing the gaps of standardization and are trying to come closer in the 10 Gb/s range. Already, IEEE 802.3av uses optical layer specifications in alignment with ITU. Some other differences are eliminated by using scrambled code, burst mode PMA and streaming FEC. The elimination of difference between TC-layer and the other standardization gaps are the main work to be done. In order to do that, ITU-T Study Group 15 and IEEE 802.3 are exchanging their ideas about coordination of the two PON standards for the next generation PONs. They indicated that this system would be based upon the 802.3av PHY and MAC layers, with ITU and Broadband Forum describing the higher layers. We hope that a coordinated 10 Gb/s PON system will come out very soon.

Long-term Future Generation PONs

If we consider long-term, where the bit rate is around several Gb/s per user, Wavelength Division Multiplexed PON (WDM-PON) is found to be the only realistic solution although it is not standardized yet. WDM-PONs have been reported with up to 32 users at 1.25 Gb/s to 2.5 Gb/s per user/wavelength, offering both great security and protocol transparency [22, 23].

In a WDM-PON, the fiber bandwidth is shared among multiple customers in the wavelength domain. WDM-PON provides an optical point-to-point connection by allocating a pair of bidirectional wavelengths to each user connected to the PON. Although the system provides higher bandwidth and security, WDM-PON is not economical enough to attract the service providers at present. In 2006, the Korean Telecom (KT) first launched WDM-PON with 100 Mb/s per wavelength in South Korea in a very short scale. Figure 10 illustrates the architecture of the basic WDM-PON.

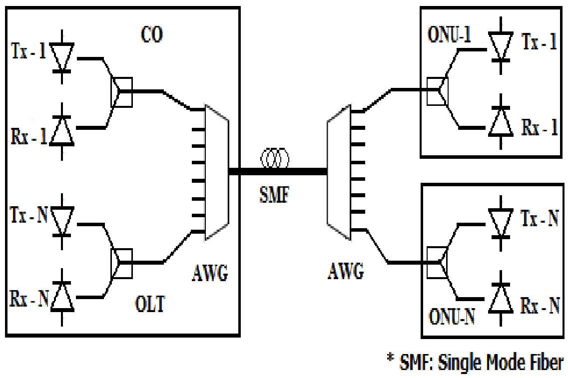


Fig. 10 Architecture of the Basic WDM-PON.

The optical power splitter in a TDM-PON is replaced with an Arrayed Waveguide Grating (AWG) to de-multiplex the downstream wavelengths and multiplex the upstream wavelengths, which allows many users to be connected to a WDM-PON. In OLT, there are an array of transmitters and receivers. Each transmitter-receiver pair is set at a wavelength of the AWG port. A feeder fiber is connected with the two AWG (One in the OLT side and the other in the ONU side). The ONUs are connected to the AWG of the distributed network. In each ONU, there is a passive splitter to separate transmitter and the receiver. Several important advantages of WDM-PON are as follows [5]:

- A WDM-PON provides a dedicated channel with higher bandwidth to individual users.
- Security issues are eliminated due to the dedicated downstream and upstream channels.
- Need for any kind of collision avoidance protocol is also eliminated.

The main limitation of WDM-PON is its higher cost due to the requirement of a wavelength specific laser for each ONU. However, research is ongoing in this regard. Several approaches have been demonstrated for the implementation of colorless ONUs in WDM-PONs such as injection-locked Fabry-Perot (FP) lasers [23,24], tunable components [25], spectral slicing [26], and Centralized Light Sources (CLSs) [27,28]. Conventional laser diodes such as FP lasers, Distributed FeedBack (DFB)/ Distributed Bragg Reflector (DFR) lasers, and Vertical Cavity Surface-Emitting Lasers (VCSELs) are normally used as transmitters. P-i-n or avalanche photodiodes are used as optical receivers. Passive splitters are commonly used for multiplexing and de-multiplexing the optical signals from/to different ONUs.

The most important enabling technologies for WDM-PONs are based on tunable components, spectral slicing, injection-locked FP lasers, and CLSs as mentioned before. Tunable components can be used in both transmitter and receiver side to provide flexibility and re-configurability of the network with minimized cost and backup stock reduction. Tunable lasers such as external cavity lasers, multi-section DFB/DBR lasers, and tunable VCSELs can be used in the transmitter side. On the contrary, tunable receivers implemented by tunable optical filter and a broadband photodiode can be used in the receiver side. The main concern of tunable components is its tuning speed and stability.

By slicing the spectrum of a Broadband Light Source (BLS), which is made of super-luminescent Light Emitting Diode (LED), Erbium Doped Fiber Amplifiers (EDFAs), or FP laser, a comb of optical signals (each with a unique wavelength) is possible. An AWG is usually deployed at the remote node (RN), which slices a narrow spectrum of the broadband optical signals, to select different wavelengths for different ONUs. Tunable filters can be used to tune the wavelengths of the optical comb. The main advantages of spectral slicing are simple implementation and low cost, while spectral slicing technique suffers from limited modulation speed, low power, and incoherent output that limits the transmission distance.

By injecting an external narrow-band optical signal into a multiple-longitudinal-mode laser such as a FP laser, the lasing mode can be locked to a single mode. The mode that is nearest to the peak wavelength of the injected optical signal will be locked to the injected light, and the other modes will be suppressed. The advantages of using injection-locked FP lasers are simplicity, low cost, and higher modulation speed, while this technique suffers from limited wavelength locking range, high power requirement, and stability.

In CLSs based approach, no light source is deployed at the ONUs; the OLT provides optical signals to ONUs, where the optical signals are modulated with the upstream data and are sent to the OLT. External modulators or Reflective Semiconductor Optical Amplifiers (R-SOAs) can be used for upstream modulation. Although CLSs based technique has the advantage of not having any transmitter in the receiver side, it has the disadvantages such as the backscattering due to Brillouin effect, the polarization sensitivity, and the high cost of the R-SOAs or optical modulators [29]. A comparison between different types of PON systems are represented in Table I.

MIGRATION TECHNIQUES FROM CURRENT STATUS TO FUTURE PON SYSTEMS

Although the current generation TDM-PONs such as E-PON and G-PON aresufficient to meet the current demands, they are not enough to meet the future demands. So, PONs with higher bit rates such as 10G-EPON, XG-PON, and WDM-PONs are expected to be deployed in the market very soon. As a result, it is a deep concern of the service providers as well as researchers, how to migrate from the current status to the future generation PONs smoothly and economically. The higher bit rates TDM-PONs such as 10G-EPON, and XG-PON are already standardized in such a way that the coexistence of E-PON/G-PON and 10G-EPON/XG-PON and their inter-operability is possible. Now, the main concern is to find a way to make TDM-PONs and WDM-PONs interoperable, which can be achieved by hybrid WDM/TDM-PONs. Researchers have proposed two types of proposals for hybrid WDM/TDM-PONs [30]: an OLT add scenario and an OLT replace scenario. These two scenarios were discussed from both the WDM and TDM approaches. The addition of Next Generation OLTs (NG-OLTs) with the present OLTs is proposed in the OLT add scenario. The NG-OLTs and present OLTs will work at the same time as shown in Figure 11 (a) [30]. The replacement of present OLTs with NG-OLTs is proposed, in the OLT replace scenario as shown in Figure 11 (b) [30].

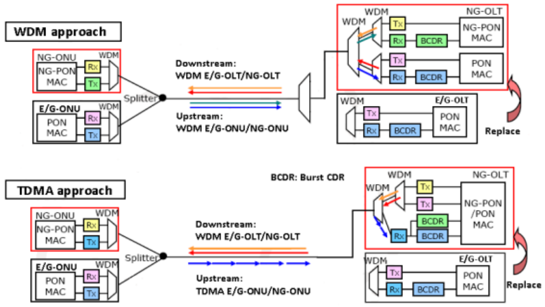
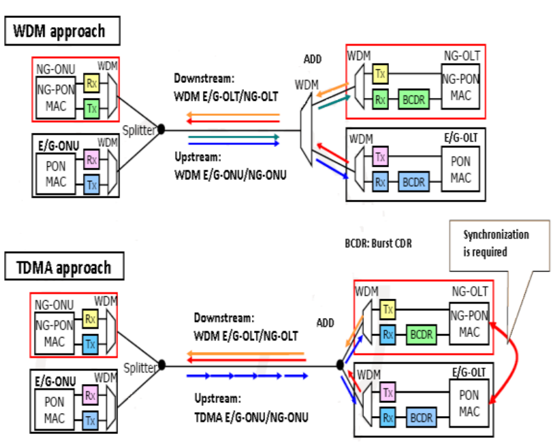


Fig. 11 Migration Scenario from the Current Generation Pons to the Next Generation Pons Systems. (a) OLT add Scenario; (b) OLT Replace Scenario [30].

Table I Comparison of Different PONs.

	TDM-PONs							Long-term Future Generation PON
	Current Generation PONs				Short-term Future Generation PONs			
	A-PON	B-PON	E-PON	G-PON	10 GE-PON	XG-PON1	XG-PON2	WDM-PON
Standards	ITU-T G.983.1	ITU-T G.983.x	IEEE 802.3ah	ITU-T G.984.x	IEEE 802.3av	ITU-T G.987.x	FSAN	No standard
Framing	ATM	ATM	Ethernet	GEM	Ethernet	GEM	GEM	Protocol independent
Maximum bandwidth	155 Mb/s (↓↑)	622 Mb/s (↓↑)	1.25 Gb/s (↓↑)	2.5 Gb/s (↓) 1.5 Gb/s (↑)	10 Gb/s (↓↑)	10 Gb/s (↓) 2.5 Gb/s (↑)	10 Gb/s (↓↑)	1-10 Gb/s per channel
User per PON	16-32	16-32	16-32	32-64	≥ 64	≥ 64	≥ 64	16-32
Bandwidth per user	10-20 Mb/s	20-40 Mb/s	30-60 Mb/s	40-80 Mb/s	≥ 100 Mb/s	≥ 100 Mb/s	≥ 100 Mb/s	1-10 Gb/s
Line coding	Scrambled NRZ	Scrambled NRZ	8b10b	Scrambled NRZ	64b66b	Scrambled NRZ	Scrambled NRZ	
Video	RF/IP	RF/IP	RF/IP	RF/IP	RF/IP	RF/IP	RF/IP	
Cost	Low	Low	Low	Medium	High	High	High	Very high



(a)

(b)

In OLT add and WDM approach, only C/L bands are available for NG-PON wavelength allocation. O band is also available with C/L band in the OLT replace and TDMA approach. Both these approaches are suitable for migration and interoperability purposes. However, OLT add and WDM approach is superior to OLT replace and TDMA approach when bandwidth allocation to an individual user is considered. Furthermore, individual E/G-OLTs and NG-OLTs are needed to be synchronized with each other in OLT add and TDMA approach, which is technically difficult. NG-OLTs require transmitters and receivers for current PONs in OLT replace and WDM approach, which

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is more expensive than OLT replace and TDMA approach [31].

In order to migrate from TDM-PONs to WDM-PONs, many researchers have reported different kinds of hybrid WDM/TDM-PON architectures [31-34]. One of the most promising solutions is proposed by the researchers of [31], where they proposed the architecture of a self-restored hybrid WDM/TDM-PON using Band Splitting WDM (BSWDM) filters that can support multiple TDM-PONs and WDM-PONs simultaneously. Another group of researchers proposed a shared tunable laser based hybrid WDM/TDM-PON, where each ONU was assigned a wavelength for a particular time slot for connecting to the OLT [32]. Long reach hybrid Dense WDM and TDM (DWDM-TDM) PON architecture was proposed in [33]. The researchers of [34] proposed a tunable laser based hybrid WDM/TDM-PON, where a coarse AWG was used to support multiple TDM-PONs and WDM-PONs. We believe that there is still scope for research in this arena.

The Convergence of optical and wireless networks are also a key research area where optical network provides high-capacity backhaul and wireless network provides flexible link to the end users [35-39]. Besides, research is ongoing on Quantum Dot Semiconductor Optical Amplifiers (QD-SOAs) [40], Thulium Doped Fiber Amplifiers (TDFAs) [41], Praseodymium Doped Fiber Amplifiers (PDFAs) [42], and Raman Amplifiers [43], in order to increase the bit rate and transmission distance. We strongly believe that, long-reach converged hybrid WDM/TDM-PON with higher bit rates will come out in near future.

CONCLUSIONS

In order to mitigate the present and future bandwidth demand, PONs have become a promising solution for access networks. Although the current generation PONs such as E-PON and G-PON are sufficient for current services, PON systems with higher bit rates are expected in order to fulfill the ever-increasing bandwidth demands from the end users. As a result, some TDM-PONs such as 10 G-EPON and XG-PONs come to the forefront of the researchers as short-term future generation PONs. On the contrary, WDM-PONs are considered as the ultimate PON systems due to its' higher system capacity and improved scalability. The standard organizations (ITU-T and IEEE) are working jointly to reduce the difference in standardization for next-generation PON systems. As a result, an interoperable and coordinated next-generation PONs are expected. We believe that, service providers will deploy hybrid WDM/TDM-PON in a large scale in near future.

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