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Review

The next generation of passive optical networks: A review

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ABSTRACT

Passive Optical Networks (PONs) have become a popular fiber access network solution because of its service transparency, cost effectiveness, energy savings, and higher security over other access networks. PON utilizes passive low-power components which removes the need for power-feeding in the fiber distribution network. This paper presents three different generations of PON that are based on the Ethernet PON and Gigabit PON standards. This article showcases the first generation of PON in terms of physical and data link layers and forms the basis for discussion about the different approaches being pursued for the next generation stage 1 PON (NG-PON1). Additionally, the main objective of this study is to review the technologies proposed for the next generation stage 2 PON (NG-PON2); highlighting the important contributions and limitations of the corresponding technologies. Hybrid approaches that combine multiple technologies are introduced as a solution to eliminate major limitations and to improve overall system-wise performance. However, NG-PON2 is still suffering from a number of challenges include cost, reach, capacity and power consumption are discussed at the end of this paper. Another purpose of this paper is to identify potential remedies that can be investigated in the future to improve the performance of the NG-PON2.

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1. Introduction

Passive Optical Networks (PONs) are a series of promising broadband access network technologies that offer enormous advantages when deployed in fiber to the home (FTTH) scenarios. The advantages include a point to multi-point architecture, high quality triple play service capabilities for data, voice and video, high speed internet access, and other services in a cost-effective manner (Ragheb and Fathallah, 2012).

Over the past decade several PON architectures have been developed by the International Telecommunications Union (ITU) and the Institute of Electrical and Electronic Engineers (IEEE). The four main PON variations developed by the ITU and IEEE can be categorized into two groups. The first kind of architecture is based on Asynchronous Transfer Mode (ATM) and includes ATM PON (APON), Broadband PON (BPON) and Gigabit PON (GPON) and the second group consists of Ethernet PON (EPON). EPON and GPON are the most popular PON variations found in use today. A conventional PON architecture is presented in Fig. 1 (Ragheb and Fathallah, 2012). In the figure, it can be seen that the PON architecture consists of an Optical Line Terminal (OLT), Optical Distribution Network (ODN), and Optical Network Units (ONU). The OLT is placed at the Central Office (CO) and connected to the splitters by fiber. The optical splitters connect to customer premises making PON a point to multi-point architecture (P2MP) (Ragheb and Fathallah, 2012).

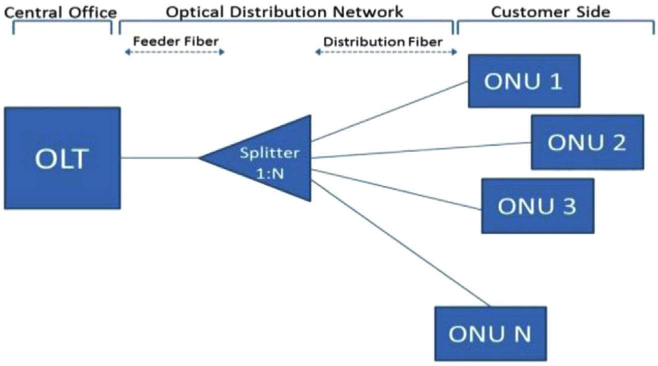


Fig. 1. PON architecture.

The EPON and the GPON standards have the same general principle in terms of framework and applications but their operation is different due to the implementation of the physical and data link layers (Olmos et al., 2011). EPON is defined by IEEE 802.3 and it is widely deployed in Asia whilst GPON is deployed in a number of other regions. GPON's requirements were defined by the Full Service Access Network (FSAN) group that was ratified as ITU-T G.984 and is implemented in North America, Europe, Middle East, and Australasia (Van Veen et al., 2011; Skubic et al., 2009).

In this paper the advancement of PON technology is classified into three generations: the first generation (deployed PON), next generation stage 1 (NG-PON1), and next generation stage 2 (NG-PON2). The evolution of the PON architectures and their corresponding capacity features are shown in Fig. 2.

The first generation of PON is based on Time Division Multiple Access (TDMA) and provides an EPON downstream rate of 1 Gbps and a GPON downstream rate of 2.4 Gbps. The NG-PON1 increases the data rate up to 10 Gbps for both standards (Biswas and Adak, 2011). There are two main scenarios to achieve an upgrade that are the upgrade from deployed EPON to XG-EPON and from deployed GPON to XG-GPON. An upgrade from deployed GPON to XG-EPON

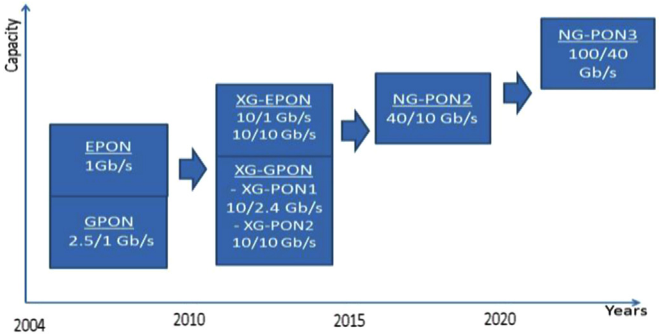


Fig. 2. PON generations.

is another potential pathway that can be considered. However, with the rapid increase in high bandwidth applications and Internet services the NG-PON1 would not be able to meet the future demand for bandwidth and Quality of Service (QoS) requirements. To find an acceptable future upgrade pathway, the research community is investigating the options for NG-PON2 and several technologies that might be used in NG-PON2 have been studied extensively in order to meet the future requirements of users and network operators (Olmos et al., 2011; Ling et al., 2010).

Four multiplexing technologies are being considered for NG-PON2 to provide a downstream transmission of 40 Gbps and upstream transmission of 10 Gbps. The technologies include high speed Time Division Multiplexing PON (TDM-PON), Wavelength Division Multiplexing PON (WDM-PON), Optical Code Division Multiplexing PON (OCDM-PON), and Orthogonal Frequency Division Multiplexing PON (OFDM-PON). The multiplexing techniques that have been identified to provide a P2MP connection between a single OLT and multiple ONUs. However, each technology has its own pros and cons (Cvijetic et al., 2010). To eradicate the multiplexing-specific limitations, hybrid approaches that combine the advantages of multiple technologies have been introduced as a dominant option for the NG-PON2. In the literature, several hybrid technologies have been studied including TDM/WDM-PON, OCDM/WDM-PON, OCDM/TDM-PON, OFDM/WDM-PON, and OFDM/TDM-PON. Among them, hybrid TDM/WDM PON (TWDM-PON) has been selected as the base element for the NG-PON2 by the FSAN community (Luo et al., 2013). The decision was made based on several factors including technology maturity, system performance, power consumption, and cost effectiveness (Luo et al., 2012, 2013).

Despite the efforts to adapt these technologies to meet the requirements of NG-PON2, challenges like increasing the capacity, reducing the cost, extending the reach and power saving still persist and required to be investigated further.

Several reviews have been published addressing PONs and its requirements. The possible solutions and prospective technologies for the NG-PONs are also suggested in (Orphanoudakis et al., 2008; Kani et al., 2009; Effenberger et al., 2009a, 2009b; Nesset, 2015; Shaddad et al., 2014; Mohamed and Ab-Rahman, 2015). However, this study reviews the different generations of PONs and focuses on the potential enabling technologies for NG-PON2. In addition, the paper outlines the major limitations and challenges of NG-PON2 technologies. This paper also studies the relevant contributions in field for the past three years that tried to accomplish the requirements of NG-PON2.

The rest of the paper is organized as follows; Section 2 presents the deployed EPON and GPON and discusses the key differences in terms of the physical and data link layers. Section 3 provides a description of NG-PON1 and outlines approaches for the improvements of the system. In Section 4, the pure technologies of PONs are discussed. Section 5 showcases the ITU-T NG-PON2 technologies including TWDM-PON and PtP WDM. In Section 6, the requirements of ITU-T standards for NG-PON2 are reviewed. Section 7 briefly reviews the recent implementation of TWDM-PON. The hybrid technologies based on XDM/WDM, XDM/TDM, and XDM/TDM/WDM are discussed in Sections 8, 10, and 9 respectively. In Section 11, major challenges of NG-PON2 are presented. Section 12 outlines reliability aspects and Section 13 outlines some of the future aspects of NG-PON2. A general discussion and several suggestions for future work are given in Section 15.

2. Deployed EPON and GPON

Although EPON and GPON provide the same services to the customers, there are some differences in the physical and data link layers, leading to some variations in the features of each standard (Tanaka et al., 2010; Ricciardi et al., 2012). Fig. 3(a) and (b) shows the structure of EPON and GPON respectively. The differences at the physical and data link layers are discussed in this section and summarized in Table 1 (Olmos et al., 2011).

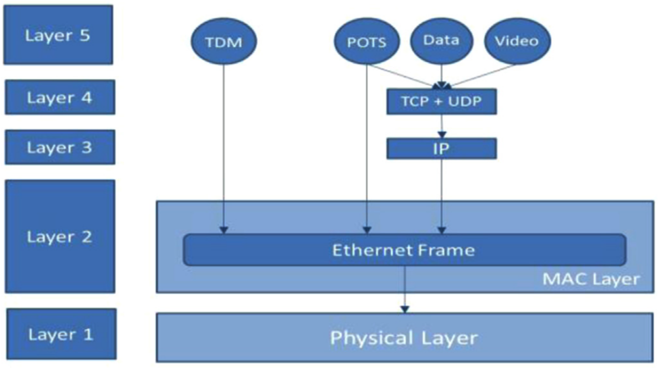
2.1. Physical layer

The variations between both standards in the physical layer include: bit rate, wavelength and splitter ratio.

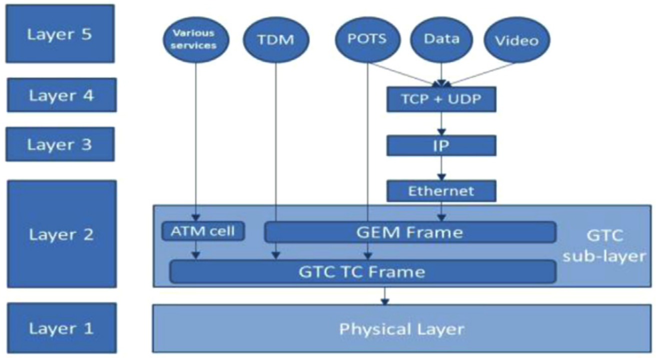
In terms of bit rate, the deployed EPON offers a bit rate of 1.2 Gbps for both downstream and upstream transmissions. However, as a result of 8B/10B line coding, the actual available bit rate is 1 Gbps (Skubic et al., 2009). In contrast, GPON supports different downstream and upstream transmission rates. For downstream transmission, GPON defines rates of 1.2 Gbps or 2.4 Gbps. Whereas for upstream transmission it offers 1.5 Gbps, 6.2 Gbps, 1.2 Gbps or 2.4 Gbps. GPON typically operates using 1.2 Gbps for upstream transmission and 2.4 Gbps for downstream transmission (Selmanovic and Skaljo, 2010).

EPON and GPON define the same wavelength bands for downstream transmission which are 1480–1500 nm and both provide a separate wavelength band for a video signal which is 1550 nm. For the upstream wavelength bands EPON uses a wavelength band of 1260–1360 nm and GPON uses a wavelength band of 1290–1330 nm (Eržen and Batagelj, 2015).

The fiber spilt ratio supported by EPON is 16 users, while, GPON supports a higher spilt ratio up to 64 users. The high split ratio supported by GPON is obtained as a result of deploying a Reach Extender (RE) at the ODN. The RE is an important concept in GPON that is utilized to increase the power budget and consequently increase the reach and the split ratio. This can be achieved by implementing technologies such as amplifiers and regenerators (Tanaka et al., 2010; Eržen and Batagelj, 2015).



(a) EPON layer structure.

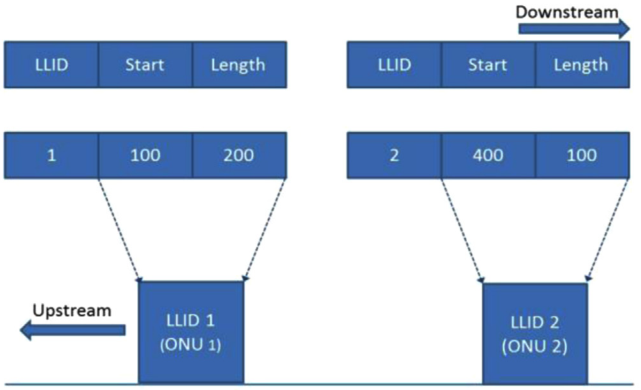


(b) GPON layer structure.

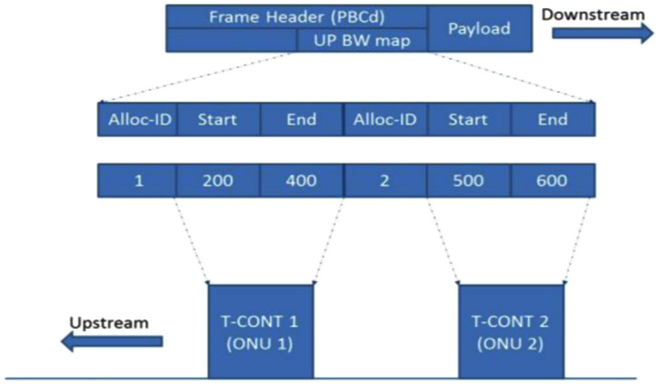
Fig. 3. Layer 2 structure (a) EPON, (b) GPON.

Table 1
EPON versus GPON.

Features	EPON	GPON
Standard	IEEE	ITU-T
Transmission speed	DS: 1.2 Gbps US: 1.2 Gbps	DS: 1.2/2.4 Gbps US: 1.5/6.2/1.2/2.4 Gbps
Split ratio	1:16	1:64
Line code	8B/10B	NRZ
Protocol	Ethernet	ATM
Security	Not guaranteed	AES
QoS	Not supported	Supported
FEC	Optional RS (255,239)	Optional RS (255,239)



(a) EPON frame structure.



(b) GPON frame structure.

Fig. 4. Frame structure (a) EPON, (b) GPON.

2.2. *Data link layer*

Fig. 4(a) presents the EPON frame structure which uses the native Ethernet frame to transmit traffic. The downstream MAC layer has the same operation as a standard Gigabit Ethernet MAC (GbE MAC), where the traffic is broadcast to all users. In the downstream frame, the preamble field contains a logical link identifier (LLID) which is a unique identifier assigned by the OLT to each ONU. The ONUs identify received traffic by matching the LLID of the received frame with its own LLID and if there is a match then it will accept the received frame, otherwise it is discarded. For upstream traffic, the MAC layer has been modified by the IEEE to operate using a TDMA approach, where the OLT assigns a specific time slot to every ONU taking into account the distance between each ONU and the OLT (Chen, 2012).

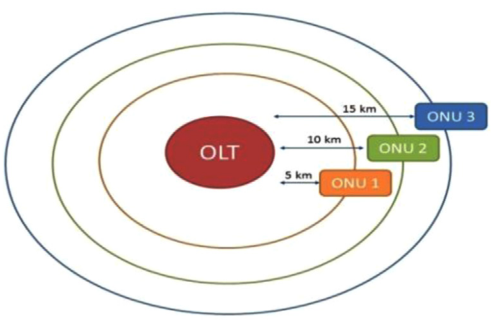
Fig. 4(b) shows the frame structure of GPON. The downstream MAC layer operates in the same manner as a GFP-framed SONET. It supports a frame of 125 μs long that uses TDM to divide the available bandwidth among the users, whilst the upstream MAC layer is based on TDMA.

GPON supports two layers of encapsulation where the Ethernet frame is encapsulated into a GPON Encapsulation Method (GEM) frame which is encapsulated again into a GPON Transmission Convergence (GTC) frame. The GTC frame also includes pure ATM cells and TDM traffic. The downstream frame is broadcast to every ONU and the ONUs use the information in the Physical Control Block downstream (PCBd) field to extract its own data. In case there is no data to be transmitted, the downstream frame will be transmitted continuously and utilized for time synchronization (Ricciardi et al., 2012). The upstream frame contains multiple transmission bursts arriving from the ONUs. Along with the payload, each of the upstream burst frames consists of the Physical Layer Overhead (PLOu), a bandwidth allocation interval which contains the Dynamic Bandwidth Report upstream (DBRu), and allocation identifiers (Alloc-IDs). When traffic reaches the OLT, ONU traffic is queued based on Classes of Service (CoS) with a diverse QoS dependent on the type of the Traffic Containers (T-CONTs) that is specified in the Alloc-ID (Segarra et al., 2013). GPON introduces five types of T-CONTs that provide QoS in the upstream direction. The T-CONT frame is used in GPON to establish a virtual connection between ONU and OLT as well as to manage fragment transmission.

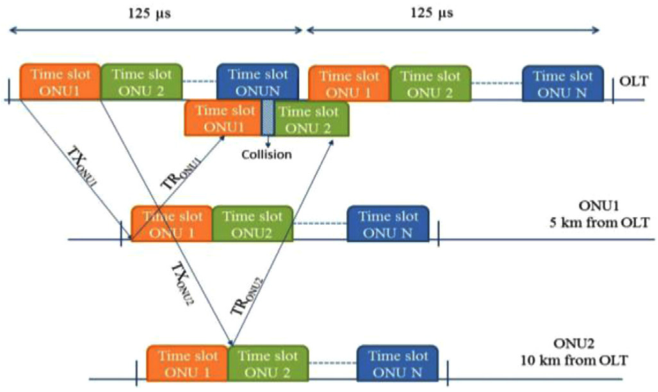
1) T-CONT type 1
   Supports fixed bandwidth that is sensitive to time. The jitter of T-CONT type-1 is 0 which enhances the suitability it has for Constant Bit Rate (CBR) traffic.
2) T-CONT type 2
   This type supports Assured bandwidth where it has a higher delay than T-CONT 1. It is used with Committed Information Rate (CIR) traffic.
3) T-CONT type 3
   Supports assured and non-assured bandwidths providing a guaranteed minimum CIR and surplus Excess Information Rate (EIR). This type is appropriate for Variable Bit Rate (VBR) traffic that does not guarantee delay.
4) T-CONT type 4
   Supports Best-Effort services such as Internet browsing, SMTP and FTP.
5) T-CONT type5
   This type is mix of all the above T-CONT types. It is appropriate for general traffic flows (Begovic et al., 2011; Tanaka et al., 2010; Ricciardi et al., 2012; Selmanovic and Skaljo, 2010).

ONUs are located at different distances from the OLT as shown in Fig. 5(a). When each ONU transmits its upstream traffic during the assigned time slot, there is a possibility that frames from different ONUs collide at some point due to the difference in propagation delay. This scenario is illustrated in Fig. 5(b). In order to guarantee that the upstream transmissions do not collide, a ranging process is performed by the OLT during the activation and registration of the ONUs. The ranging process is based on calculating a specific delay time for each ONU according to its distance from the OLT to equalize its transmission delay with other ONUs. This delay is called Equalization Delay (ED). Each ONU will store and apply its ED to all the upstream transmissions. The ED values are broadcast to other ONUs using Physical Layer Operations and Maintenance (PLOAM) messages and each ONU resumes its transmission based on the ED. Fig. 6 shows an ONU in a ranging state. While one ONU is active and sending traffic, transmissions from other ONUs must be suspended (Kramer, 1999).

Multipoint control protocol (MPCP) has been introduced to facilitate dynamic bandwidth allocation process. This is executed at the MAC layer (Chochliouros, 2009). For EPON, MPCP can be run



(a) ONUs at different location from OLT



(b) ONUs upstream collision [24]

Fig. 5. (a) ONUs at different location from OLT. (b) ONUs upstream collision (Kramer, 1999).

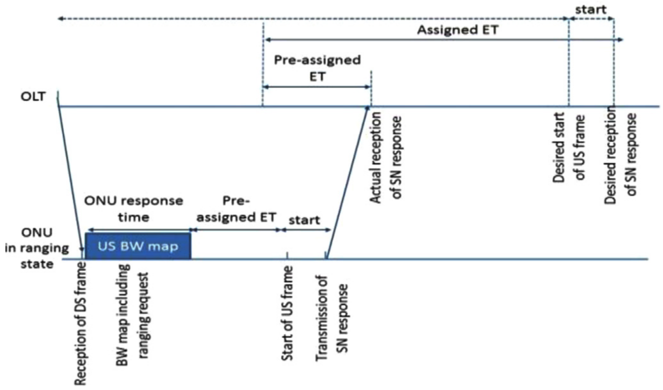


Fig. 6. Ranging state (Kramer, 1999).

in one of the two modes. Firstly, in the normal mode, it makes use of the two control messages to control the allocation of bandwidth, which are GATE and REPORT messages. In the downstream direction, the GATE messages travel from the OLT to ONUs and carry the allocated bandwidth information (Chochliouros, 2009). In the upstream direction, the REPORT messages that contain bandwidth request information are sent by ONUs to the OLT. A specific algorithm is used to determine the grant allocation for each of the ONU (Chen, 2012). The second mode is the auto-discovery. It is based on three control messages that are REGISTER, REGISTER_REQUEST, and REGISTER_ACK. These messages are used to discover and register a new ONU. In addition, it reports information about the ONU including MAC address and round trip delays (Chochliouros, 2009). In the GPON scenario, grant messages are sent based on T-CONT. Like EPON, MPCP protocol is implemented to facilitate the dynamic bandwidth allocation in GPON. Two main approaches supported in GPON to deduce the occupancy of the buffer status of each T-CONT which are status-reporting Dynamic Bandwidth Allocation (DBA) and traffic-monitoring DBA. In the case of status-reporting DBA, each ONU directly sends status report information to the OLT. Whereas, in the traffic monitoring DBA, the inference of the T-CONT's buffer status at the OLT is reliant on the historical information of bandwidth use and the amount of defined bandwidth. The header in the downstream frame includes the upstream bandwidth map (BW map) field that depicts the start and end time for upstream transmission for each ONU (Skubic et al., 2009; Ansari and Zhang, 2013).

3. NG-PON 1

NG-PON1 has been introduced to attain bit rate up to 10 Gbps. The possible scenarios for the upgrade are discussed in this section (Begovic et al., 2011).

3.1. *From EPON to XG-EPON*

XG-EPON inherits many features from the deployed EPON. However, some modifications at the physical layer are required. These modifications are summarized in Table 2 (Gorshe and Mandin, 2009).

In terms of bit rate, XG-EPON supports two physical layer modes. The first one is symmetric transmission with 10 Gbps. The second mode is asymmetric transmission with 10 Gbps for downstream transmission and 1 Gbps for upstream transmission (Gorshe and Mandin, 2009). The XG-EPON uses the wavelength band 1260–1280 nm for upstream traffic and the wavelength band 1575-1580 nm for downstream traffic. The line coding applied in XG-EPON is 64B/66B, which is an improved version of 8B/10B. Thus, it reduces the bit-to-baud overhead from 20% to 3%. Moreover, FEC was optional in deployed EPON but has become a compulsory requirement for XG-EPON with the use of RS (255, 223). The supported XG-EPON split ratios are 1:16 with a distance of at least 10 km and a split ratio of 1:32 with a distance of at least 20 km (Tanaka et al., 2010).

The TDM technique used in EPON enables the deployed EPON and the XG-EPON to coexist. However, a multi-rate OLT is required to provide pre-amplification by utilizing semiconductor optical amplifiers (SOA) (Olmos et al., 2011).

3.2. *From GPON to XG-GPON*

XG-GPON has similar characteristics to the deployed GPON with some variations in the physical layer that lead to considerable performance improvements. These include split ratio, power budget, and reachability (see Table 3). The data link layer framing and management process have not changed which results in reduced migration complexity.

Table 2
G-EPON VS XG-EPON.

Feature	GPON	XG-GPON
Bit rate	2.4/1.2 Gbps	XG-GPON1: Asymmetric 10/2.5 Gbps XG-GPON2: Symmetric 10 Gbps
Wavelength (nm)	US: 1290–1330 DS: 1480–1500	US: 1260–1280 DS: 1575–1580
FEC	Optional	
SR (255,239)	RS (255, 223)	

Table 3
1G-EPON VS XG-EPON.

Feature	1G-EPON	XG-EPON
Bit rate	Symmetric 1Gbps	Symmetric 10Gbps Asymmetric 10/1Gbps
Wavelength (nm)	US: 1260–1360 DS: 1480–1500	US: 1260–1280 DS: 1575–1580
Line code	8B/10B	64B/66B
FEC	Optional SR (255,239)	Mandatory RS (255, 223)

The XG-GPON is divided into two classes. The first class called XG-GPON1 provides asymmetrical transmission with 10 Gbps downstream and 2.5 Gbps upstream. The second class is XG-GPON2 which provides 10 Gbps symmetrical transmission (Eržen and Batagelj, 2015; Leng et al., 2013). Details about the XG-GPON1 physical layer have been described in ITU-T G.987.2. Whereas, the XG-GPON2 physical layer standard is still to be finalized.

1) XG-GPON1
According to the G.987.1 recommendation for XG-GPON1, two scenarios have been proposed to enable migration from GPON to XG-GPON1. The first scenario is a green-field migration which is the replacement of the copper connection into premises with an optical connection. The other option is the PON brown-field migration scenario which is an upgrade of the existing GPON system and this includes replacing or upgrading some of the network components such as ONU units or OLT modules if necessary (Eržen and Batagelj, 2015).
The downstream wavelength band selected for XG-GPON1 is between 1575 and 1580 nm and the upstream wavelength band is between 1260 and 1280 nm. The wavelength bands were selected to enlarge the guard band between the wavelengths which reduces signal interference (Eržen and Batagelj, 2015).
The coexistence of XG-GPON1 with the deployed GPON is an important criterion when an upgrade is considered. Even though this approach decreases the overall cost, there is an additional cost associated with wavelength filtering that is required at the ONUs. Fig. 7 shows the coexistence scenario, where the CO consists of two OLTs, one to carry the GPON connection and the other to carry the XG-GPON1 connection. New equipment named as WDMr1 is installed at the CO. Multiplexing/demultiplexing the signal of both OLTs and RF is its functionality. On the user's side, a Wavelength Blocking Filter (WBF) is required in order to differentiate the PON data traffic (Eržen and Batagelj, 2015; Galveias, 2012).

2) XG-GPON2
The major aim of XG-GPON2 is to offer symmetrical transmission by increasing the upstream transmission up to 10 Gbps.
The expectation of spontaneous movement from GPON to the XG-GPON1/XG-GPON2 has been discussed in the literature. However, a number of drawbacks associated with the coexistence of these technologies have appeared. This approach requires different receivers at the OLT in order to receive the upstream data at different transmission speeds. In addition, it is not certain that the fragmentation process will be supported at a higher transmission rate in the upstream transmission (Kataoka et al., 2011).

3.3. Mixed scenario

The mixed scenario is another possible upgrade to NG-PON1. In this platform, GPON and XG-EPON coexist with each other and operate on the same infrastructure. However, this scenario requires suitable wavelength band separation with the help of a WDM filter at the OLT in order to eliminate interference (Kataoka et al., 2011).

4. ING-PON2 pure technologies

Studies have been conducted for several NG-PON2 technologies that offer up to 100 Gbps. This includes high speed TDM-PON, WDM-PON, OCDM-PON, OFDM-PON, and hybrid technologies (Cvijetic et al., 2010; Luo et al., 2012). The pure technologies will be reviewed in this section.

4.1. High speed TDM-PON

TDM-PON allows multiple users to share the same bandwidth using a single wavelength. A typical TDM-PON structure is shown in Fig. 8. The downstream traffic is broadcast to all users and a specific time is assigned by the OLT to every ONU to control upstream transmissions. These time slots are allocated in downstream and upstream frames where a complex algorithm is required to arrange and assign the bandwidth in order to avoid collisions (Esmail and Fathallah, 2013; Muciaccia et al., 2014).

TDM-PON is a simple and cost effective technology, however; it has limited scalability due to the fact that ONUs share bandwidth.

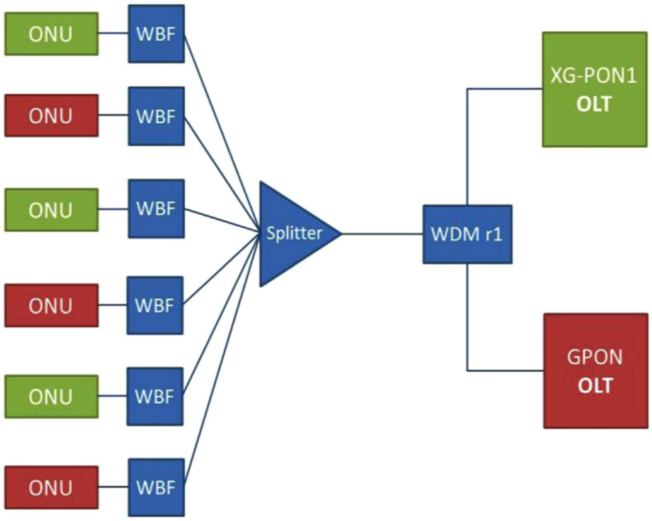


Fig. 7. Coexistence of GPON and XG-PON1.

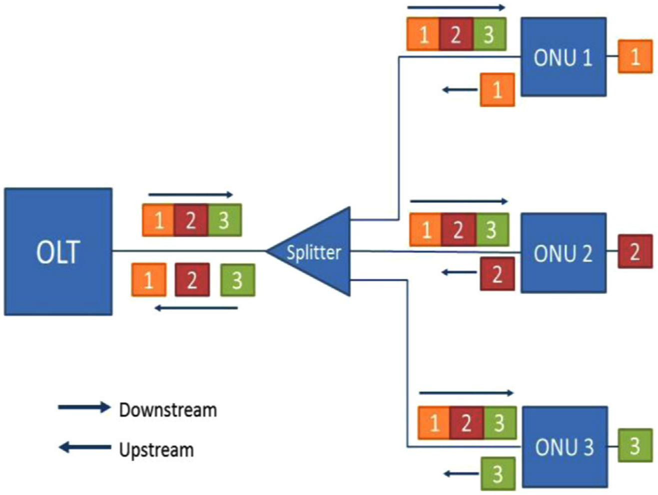


Fig. 8. TDM architecture.

Increasing the bit rate for all of the users will be a challenging task because every ONU receiver operates at a bit rate that is higher than the bit rate assigned per ONU. Utilizing a high speed digital signal processor and field-programmable gate array to increase the bitrate to higher than 10 Gbps increases cost and complexity (Muciaccia et al., 2014; Sotiropoulos et al., 2013). In addition, TDM-PON is not very secure due to the shared infrastructure which opens the possibility of eavesdropping and other attacks. Moreover, the variation in the distance between ONUs and the OLT is another drawback that causes variation in the optical power and consequently, the OLT receiver operates in burst mode (Hara et al., 2010; Yoshima et al., 2012).

In order to upgrade the current TDM-PON to meet the NG-PON2 requirements, a number of approaches have been investigated to increase the capacity of TDM-PON, including:

- Conventional ON OFF Key (OOK) systems: Applying OOK is the easiest way to increase the capacity of TDM-PON. However, this solution is not favorable for future PONs because it requires a 40 Gbps burst-mode receiver, high cost 40 GHz electronics and photonics as well as it requires highly sensitive receivers (Sotiropoulos et al., 2013).
- Due-binary modulation: this scheme is similar to the deployed PON system that uses one wavelength for downstream and another one for upstream. Invest such modulation in the downstream grants the ONUs with 20 GHz bandwidth and reduce the disruption (Nesset, 2015).
- Bit interleaving: This approach employs two wavelengths, one for downstream that supports a 40 Gbps signal and another wavelength for upstream transmission that supports 10 Gbps. Bit interleaving is introduced in the downstream frame where each ONU is pre-assigned an offset and an interval. This technique requires the ONU receiver operating at a rate lower than 40 Gbps. It simplifies the transmission process, reduces power consumption, and reduces the electronic circuitry of the ONU receiver (Luo et al., 2012).
- Serial 40G NRZ- 40G serial Non-Return-To-Zero (NRZ): is another approach that has been investigated to increase the capacity of legacy TDM-PON. However, it has a transmission distance limitation due to chromatic dispersion and the associated optical power requirement at the receiver (Srivastava, 2013).

4.2. WDM-PON

WDM-PON has been considered as an alternative technology to TDM-PON. A typical WDM-PON structure is shown in Fig. 9. It provides a virtual point–to-point connection between the OLT and several ONUs; where, each ONU is assigned a different wavelength for transmission.

The major difference between the implementation of WDM-PON and TDM-PON is that WDM-PON employs a WDM device in the ODN such as an Array Wavelength Gratings (AWG) instead of a power splitter. This leads to dramatic reduction in the power loss and consequently supports a large number of ONUs (Nesset, 2015). This type of WDM is called Wavelength routed. Each port of the AWG is assigned to a specific wavelength; each transmitter at the ONU transmits a signal on the wavelength that is specified by the port. This architecture offers lower insertion loss and a simple ONU receiver structure. However, the OLT is required to install a standard receiver and a wavelength de-multiplexing device.

Upstream transmission in a WDM loop back structure is achieved by utilizing a single or two fiber link. In the case of a single fiber link, bidirectional transmission of the light and the modulated signal leads to Rayleigh Backscattering (RB) noise. This issue affects the performance of downstream and upstream transmissions (Duan et al., 2013) and consequently degrades the transmission distance and the receiver sensitivity (Feng et al., 2014).

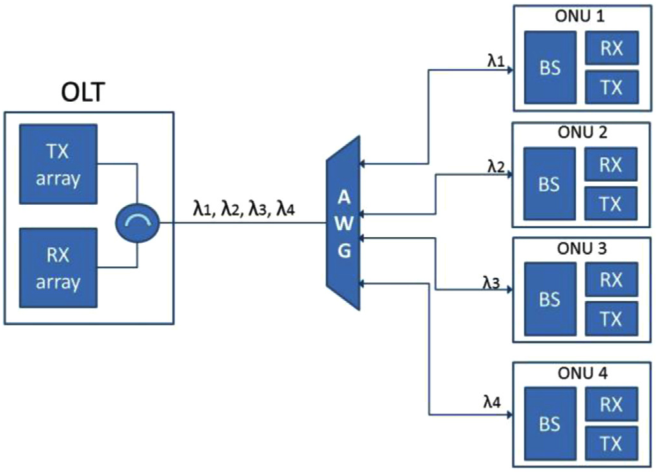


Fig. 9. WDM-PON.

There are several schemes that can be used to mitigate RB noise, for example:

- Using phase modulation. In (Chow and Yeh, 2013) the authors claim that the RB noise can be reduced by using Wavelength-Shifted amplitude-shift keying (WS-ASK) modulation. In addition, the role of phase modulation non return to zero (PM-NRZ) modulation format has been investigated in (Talli et al., 2008) to reduce BR noise which can be farther reduced by utilizing an optical filter.
- Using dual parallel Mach-Zehnder modulator (DP-MZM)
- Four-wave mixing (FWM).

A key advantage of WDM-PON is that it allows every ONU to transmit at the peak speed as the OLT bandwidth is not shared. Thus, it is capable of supporting a higher data rate (Yoshima et al., 2012; Srivastava, 2013). Another type of WDM-PON is based on splitter and known as WDM-PON wavelength switched in which the power splitter is implemented to distribute incoming signals equally into all ONUs. However, each ONU is required to equip with a wavelength filter to select specific wavelength. Although wavelength switched PON considers simple and distributed structure, its signal loss is higher than wavelength routed PON (Banerjee et al., 2005).WDM-PON is classified into two classes based on the number of wavelengths supported and the wavelength spacing between the individual wavelengths transmitted over a single fiber. The first class is Dense WDM (DWDM) and its wavelength plan is defined by ITU-T G.694.1 and the second class is Coarse WDM (CWDM) and its wavelength plan is defined by ITU-T G.694.2. The main objective of DWDM is to increase the network capacity by minimizing the wavelength spacing; CWDM aims to reduce the cost where the wavelength spacing is sufficiently high to permit the transmitters to be more accurately controlled (Muciaccia et al., 2014; Ragheb and Fathallah, 2011).

In the literature, there are number of approaches that have been proposed to be implemented in WDM-PON. The approaches are discussed below.

1) Externally seeded WDM-PON (Sotiropoulos et al., 2013): In a wavelength-splitter based ODN, a light source is splitted spectrally and distributed to reflective ONUs. This approach is mature and available with the commercially existing systems. However, the commercially available systems require that the

wavelength splitter operate over the power splitter, which imposes the major challenge in terms of link budget. Additionally, the possibility of attaining more than 1 Gbps of data rate is not clear as it exceeds the capability of the current system (Nesset, 2015).

2) Wavelength re-use WDM-PON (Nesset, 2015): This approach assigns a wavelength to each user for downstream and upstream transmission. The re-use of the wavelength is enabled by the transmitter based on semiconductor amplifier. This amplifier modulates the downstream signal in inverse Return-to-Zero format and the upstream signal in Return-to-Zero format (Nesset, 2015).
3) Tunable WDM-PON (Begovic et al., 2011): This approach is based on a low cost tunable transmitter module instead of the conventional module. The reduction of the cost is achieved by removing thermoelectric coolers and the wave-lockers from the conventional modules. Tuning at the upstream is performed utilizing the shared OLT based wave-locker. However, tunable receivers are needed at each ONU to perform colorless function (Nesset, 2015).
4) Ultra-dense Coherent WDM-PON (Begovic et al., 2011): This approach is based on coherent detection where the channels are tightly spaced (around 3 GHz). 1 Gbps data rate is allocated to every user utilizing dedicated Quadrature Phase Shift Keying (QPSK) modulated wavelength. However, the transmitters and the receivers are very complex systems and expensive. Thus, more improvements in photonic integration are essential to be used in practical implementation (Nesset, 2015).
5) Self-seeded WDM-PON (Tanaka et al., 2010): In this scheme, the seed light of the ONU is self-generated by a reflector at the common port of the wavelength splitter. However, the length of the drop fiber (the fiber between the splitter and the ONU) is limited (Nesset, 2015).

Several schemes have been proposed to allow migration from TDM-PON to WDM-PON. Hybrid TDM/WDM PON or SUCCESS-HPON (The Stanford University aCCESS) provides a cost effective and smooth migration path from TDM to WDM. SUCCESS-HPON is based on the lasers at ONUs and shares tunable WDM components at the OLT. Hence, it achieves bandwidth equivalent to the pure WDM-PON bandwidth with lower costs (Gutierrez et al., 2005).

In (Chow and Yeh, 2013), another migration scheme has been proposed. In this scheme, the differential phase-shift keying (DPSK) technique is used for the downstream signal. The wavelength-shifted amplitude-shift keying (WS-ASK) is used for the upstream signal. At the ONU, an optical filter is implemented to select the intended downstream wavelength and to demodulate the downstream signal. The upstream signal is generated by signal demodulation that is based on reusing the downstream wavelength. Another benefit of this scheme, beside the smooth migration, is that it does not require any changes to the existing fiber infrastructure.

In (Shachaf et al., 2007), a multi-PON architecture based on a coarse AWG at the OLT has been introduced to allow smooth migration path from TDM-PON to WDM-PON. The AWG is designed to support several TDM-PON and WDM-PON by employing tunable laser at the OLT. In addition, the splitter in the distribution side is replaced by a multiplexing unit that works to justify parallel processes of TDM-PON and WDM-PON. This provides the required bandwidth for the ONUs. At the ONU side, RSOAs is required to implement colorless transceivers, hence, no change is needed at the customers' side.

The multiple-wavelength characteristic in WDM-PON offers several unique features. Firstly, each user can upgrade its capacity without the need for pre-designing a new fiber. Furthermore, the upgrade will not impact other users. Secondly, security is improved and the potential eavesdropping issue is eliminated (Srivastava, 2013; Urata et al., 2012).

Despite these features, a number of restrictions make WDM-PON an inappropriate technology for NG-PON2. With the limitation of the number of wavelengths allowed in the system and with the large bandwidth requirement, it leads to inefficient utilization of the bandwidth (Hernandez et al., 2012). Additionally, the cost is a prominent issue in WDM-PON where it increases due to the need for extra equipment such as colored ONUs and a transceiver for every wavelength at the OLT (Sotiropoulos et al., 2013; Urata et al., 2012).

4.3. *OCDM-PON*

Introducing OCDM-PON technology leads to considerable improvements for NG-PON2. The advantages include highly efficient use of bandwidth, good correlation performance, asynchronous transmission, flexibility of user allocation, low signal processing latency as well as improving network security (Yoshima et al., 2013; Kataoka et al., 2010).

OCDM can be classified into two main categories: coherent system and incoherent system. In coherent system, OCDM is implemented through a bipolar approach that requires information about the phase of the carriers. On the other hand, the incoherent system is implemented through a unipolar approach. Owing to the simplicity of incoherent hardware as well as its non-reliance on phase synchronization detection, incoherent system has emerged as the preferred detection scheme. Fig. 10 shows the basic structure of the OCDM network, which has four main components including transmitter, encoder, decoder, and the receiver. At the transmitter, an information source provides a data bit for a laser at every T second. The encoder then multiplies the data bit “when it equals 1” by a code-word. The code-word can be formed by one-dimensional encoding using the time or wavelength domain or by a two-dimensional encoding scheme, which is a combination of both domains. Yet, recent studies have shown advantages of three dimensional codes (Yen and Chen, 2015; Wang and Chang, 2015; Jindal and Gupta, 2012; Garg and Kaler, 2013; Shum, 2015). The pulses generated are referred to as chips and have a duration of $Tc=T/n$, where T donates the duration of each bit and n denotes the code length.

The multiplexed signal is broadcast to all of the users. The signal arrives at the receiver and passes through the decoder. The decoder matches the code and accepts only the intended user's signal. Then the output of the decoder passes through photodetection and integration. Later, the output power is sampled for each bit interval and compared to the threshold value to provide

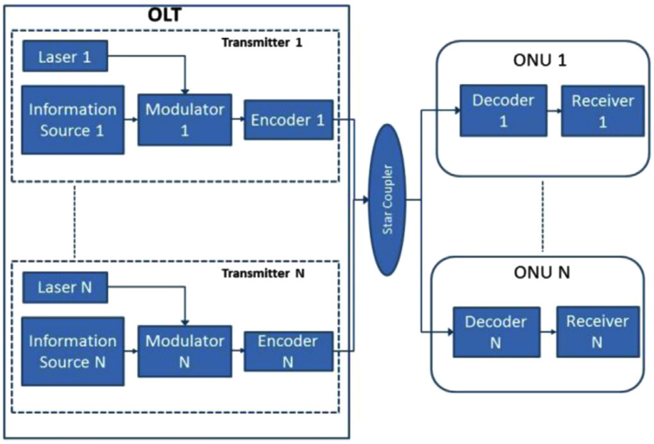


Fig. 10. OCDM architecture.

Table 4
Types of OCDM codes.

	Name of encoding	Bipolar/ Unipolar	Coherent/ incoherent	Codes
1D Code	Pulse amplitude	Unipolar	Incoherent	– OOC – PC – QCC – HCC
	Pulse phase	Bipolar	Coherent	– M-sequence
	Spectral amplitude	Unipolar	Incoherent	– Gold code
	Spectral Phase	Bipolar	Coherent	– Walsh-Hadamard Codes
2D Code	Wavelength-Hopping Time spreading	Unipolar	Incoherent	2-D WH/TS OOC
	Space encoding	Unipolar	Incoherent	2-D Space Codes
3D Code	Three dimension encoding	Unipolar codes	Incoherent	Space/time/ wavelength or Polarization/time/wavelength codes

an estimation of the transmitted bit (Zahedi and Salehi, 2000; Anaman and Prince, 2012).

The performance of the OCDM network is reliant on the performance of the address codes that have been designed to be orthogonal in order to reduce Multiple-Access Interference (MAI) and performance of the receiver structure that must successfully operate in an environment including various noise sources (Sri and Sundararajan, 2013; Zahedi and Salehi, 2000).

Various types of codes have been investigated and the codes and corresponding coding devices are shown in Table 4 (Yin and D, 2007). In Table 5 a comparison of different OCDM receiver structures is presented (Zahedi and Salehi, 2000).

4.4. OFDM-PON

OFDM-PON is considered as the most attractive system because of its scalability and ability to provide bit rate up to 40 Gbps per user. OFDM for NG-PON2 is used as multiplexing technique as it is spectrally efficient modulation method. OFDM technique offers flexibility on dynamic bandwidth allocation, enables multiple services, and attains high spectral efficiency. OFDM utilizes a large number of orthogonal subcarriers that are closely–spaced in order to carry traffic. These subcarriers are modulated at a low symbol rate utilizing conventional or advanced modulation techniques (Muciaccia et al., 2014).

OFDM-PON architecture is similar to the conventional PON. It utilizes two different wavelengths for downstream and upstream transmissions (Shaddad et al., 2014). The OLT generates multiple orthogonal subcarriers that are assigned to different ONUs. Each subcarrier is divided into different time slots. The OLT performs the partitioning process and distribute the total bandwidth over the subcarriers, over the timeslots or on both to different ONUs according to their demand. For downstream transmission, each ONU recognizes its own OFDM subcarriers and/or time slots based on information obtained by the OLT's schedule. For upstream transmission, the OLT works to assemble the sub-frames coming from different ONUs to generate a complete OFDMA frame (Cvijetic, 2012, 2010).

Various benefits can be achieved by applying the OFDM multiplexing technique. Firstly, the total cost is reduced because of the cost of the complex optical modulation at the OLT can be shared between the users. In addition, the ONU implements a simple and inexpensive optical modulation in order to identify data for that ONU. Moreover, OFDM-PON technology helps to reduce the cost by using cost-effective electronic devices instead of optical devices. The overlapping characteristic of OFDM produces no interference which results in the effective utilization of the spectral resources. Furthermore, in comparison with other technologies, OFDM-PON provides a two dimensional bandwidth map with finer granularity, offering flexibility for assigning the bandwidth at different levels.

Despite the enormous advantages of OFDM, some limitations have been identified. OFDM-PON requires complex receivers that are reliant on high speed DSP and FPGAs. Furthermore, OFDM-PON is disadvantaged by noise and a high Peak Average Power Ratio (PAPR). The PAPR issue appears as a result of sinusoidal signals from multiple OFDM subcarriers that interfere constructively in the time domain. This generates a higher amplitude value than the average amplitude value of the signal. The noise is generated as a result of interference when multiple signals from multiple users are detected on the photodiode at the OLT. Such interference leads to performance degradation (Cvijetic, 2012; Cano et al., 2013). Frequency offset is also a disadvantage of OFDM technique which occurs due to mismatch of carrier frequencies (Bindhaiq et al., 2015).

4.5. UNI-PON

High costs, wastage of resources are the main limitations in the existing multiplexing techniques insist researchers to think about more appropriate and effective methods. Some researchers came-up with the idea of UNI-PON (Cloud-Radio Access Network [Online]).

In UNI-PON data manipulation is done at OLT using cloud computing. The advantages of UNI-PON include access of all services for all users, lower cost, and connectivity of radio remote units, multi-rate adjustment, and dynamic bandwidth allocation. In (Liu et al., 2012), a physical layer adaptive algorithm is used to attain multi-rate and dynamic bandwidth allocation. With the rapid advancement in technology the systems should be resilient to adopt future changes. Therefore, UNI-PON can be a suitable choice for future networks.

Table 5
comparison of several reciever structures.

Receiver structure	Characteristics
Passive correlation receiver	Cheap, not suitable for high speed applications , high power loss
Active correlation receiver	Expensive, supports high speed applications.
Optical hard limiter and passive correlation receiver	Not suitable for high speed applications, relies on the availability of optical hard limiter
Optical hard limiter and active correlation receiver	Supports high speed applications, relies on the availability of an optical hard limiter
Double optical hard limiter and passive correlation receiver	Not suitable for high speed applications, expensive, good performance.
Double optical hard limiter and active correlation receiver	Supports medium to high speed applications, high power loss
High speed chip detector	Not suitable for high speed applications, low power loss

4.6. PDM-PON

PDM-PON technology uses orthogonal polarizations at the same wavelength. It is capacity efficient but due to the polarization behavior in the fiber, it would be very hard to separate the signals at the receiving end (Muciaccia et al., 2014).

5. ITU-T NG-PON2 technology

5.1. TWDM-PON

In April 2012, hybrid TDM and WDM (TWDM-PON) technology was selected as the multiplexing technique for NG-PON2 by the FSAN community (Luo et al., 2013). The decision was made based on several factors including; technology maturity, system performance, power consumption and cost (Luo et al., 2012). In July 2013, the selection of TWDM-PON was confirmed by ITU-T “under the G.989 series” and it was named as NG-PON2 (Murano, 2014).

TWDM-PON combines the advantages of the high capacity provided by TDM and the large number of wavelengths provided by WDM into one architecture by transmitting TDM frames to several users over several wavelengths (Ragheb and Fathallah, 2011; Hernandez et al., 2012).

The basic structure of TWDM-PON consists of four techniques of XG-GPON1s. They are stacked by utilizing four pairs of wavelengths. Fig. 11 shows TWDM-PON and the wavelength pairs that are “{λ1, λ5}, {λ2, λ6}, {λ3, λ7} and {λ4, λ8}” (ITU-T, G.989.1, 2014). Each XG-GPON1 provides 10 Gbps and 2.5Gbps of data rate in downstream and upstream transmissions respectively. Thus, TWDM-PON increases the bit rate up to 40 Gbps for downstream transmission and 10 Gbps for upstream transmission (Luo et al., 2013).

Implementing a simple network requires that each ONU is equipped with programmable transmitter and receiver that can be tuned to any wavelengths (ITU-T, G.989.1, 2014). Additionally, such a network requires an optical amplifier at the OLT in order to promote the downstream signal and to pre-amplify the upstream signals. Therefore, TWDM-PON obtains a higher power budget than XG-GPON1. The ODN is still passive where OLT is equipped with the amplifier, multiplexor, and the de-multiplexor (Luo et al., 2013).

Another implementation of TWDM-PON is referred to as wavelength routed hybrid PON that works by combining the power splitters and AWG (see Fig. 12). This configuration makes use of identical colorless ONUs and supports a higher number of wavelengths than the stacked PON (Kramer et al., 2012).

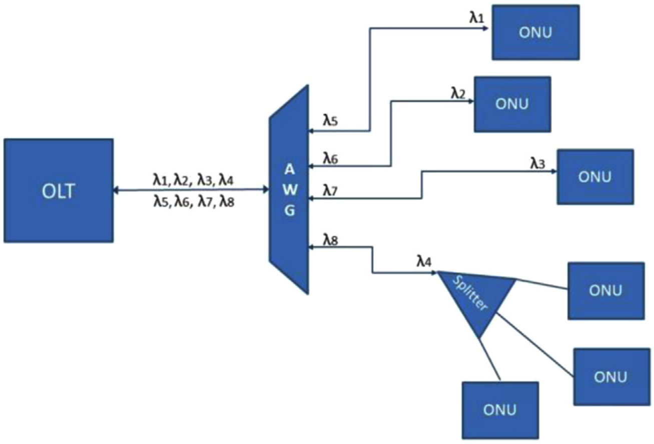


Fig. 12. Wavelength routed hybrid PON.

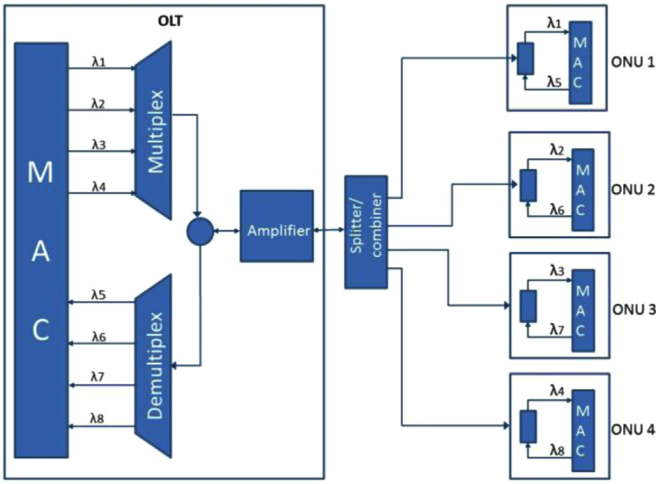


Fig. 11. TWDM-PON.

TWDM-PON is broadly classified into static and dynamic approaches. For the static approach, the downstream and upstream wavelengths specified for ONUs are static and do not change during the process. On the other hand, in the dynamic approach the wavelength is able to change dynamically based on operation and communication needs. As a result of frequent changes in wavelengths, ONUs are required to deploy burst mode receivers. However, the dynamic approach has advantages over the static counterpart because it allows load balancing, power saving, and resilience (Ragheb and Fathallah, 2011).

A major limitation of the TWDM-PON is the Crosstalk issue that rises up due to the rival power from the multiple ONUs. A significant crosstalk occurs at OLT receiver due to staking of a multiple wavelength channels and the presence of dynamic power range at the upstream transmission (Bonk et al., 2015).

Several studies have been conducted addressing this issue. In (Poehlmann et al., 2014), the sources of crosstalk in the upstream transmission have been analyzed and a number of requirements at the OLT receiver have been introduced. The paper analyzes three cases of crosstalk in TWDM-PON, each with specific requirements. The cases are discussed below.

- Case 1: When ONUs not-transmitting (WNT).
- Case 2: Insufficient isolation of WDM channels in the wavelength demultiplexer (WM) of the OLT receiver (IWM).
- Case 3: out-of channel optical power from neighboring channels (OCP).

In addition, the paper proposes mitigations in case of the requirements are difficult to realize.

In (Han Hyub et al., 2014), two methods of ONU power leaving to mitigate the inter channel crosstalk of TWDM-PON in the upstream transmission have been proposed. The first method is based on transmitter bias current and/or modulation current that are low cost method. The other method is based on implementing SOA or variable optical attenuator (VOA) in the transmitter.

In TWDM-PON, ONUs required to be colorless to enable re-use of the wavelength. RSOA ONU optical transceiver is considered as the most preferable option amongst other colorless ONU due to its simplicity and colorlessness. It helps to eliminate the volume provisioning problem of the ONUs in the WDM-PON. However, RSOA ONU leads to impairments when operating in full-duplex mode. Numbers of approaches to address the optical modulation formats and compensating techniques have been proposed to overcome the bandwidth noise and crosstalk challenges (Schrenk et al., 2009; Papagiannakis et al., 2010; Polo et al., 2008; Omella et al., 2010; Cano et al., 2010; Schrenk et al., 2009; Prat et al., 2011; Omella et al., 2009; Schrenk et al., 2012).

Another issue must be considered while developing the TWDM-PON is the efficient dynamic bandwidth and wavelength allocation (DBWA). Several algorithms have discussed in the literature including Earliest Finish Time (EFT), Earliest Finish Time with Void Filling (EFTVF) (Buttaboni et al., 2013; Dias et al., 2014), OFF-DWBA and ON-DWBA (Dias et al., 2015). Additionally, some of DBWA algorithm have been presented based on particular network architecture (Buttaboni et al., 2013) such as Optical Burst Switching DBA (OBS-DBA). This algorithm has been designed for SARDANA network (Segarra et al., 2008), Slotted Medium Access Control (SMAC) for Slotted PON (SPON) (Hui-Tang et al., 2009), and STARGATE EPON (Meng et al., 2009).

5.2. *Point-to-Point WDM Overlay*

Point to Point WDM Overlay (PtP WDM) is a method for NG-PON2 that realizes the operator requirements and supports business and backhaul services. The basic configuration of PtP WDM has eight channels of PtP WDM, which enables co-existence with legacy PON systems. Based on the deployed configuration, network operator is able to assign unused spectrum to the additional PtP WDM channel. Similarly, in TWDM-PON the ONUs needs to implement a tunable transmitter and receiver (Nesset, 2015).

6. ITU-T Standards for NG-PON2

According to ITU-T G.989.2 (physical layer specification), NG-PON2 is a PON system that consists of a set of TWDM channels and/or a set of PtP WDM channels. The TWDM channel is a pair of one downstream wavelength channel and one upstream wavelength channel that enable P2MP connectivity. Whereas, the PtP WDM channel is a pair of one downstream wavelength channel and one upstream wavelength channel offering P2P connectivity. This section discusses the main characteristics of the physical layer of NG-PON2 (ITU-T, G.989.1, 2014).

6.1. *Wavelength band*

Table 6 shows the ITU-T G.989.2 wavelengths bands for both TWDM-PON and PtP WDM-PON.

For TWDM-PON downstream, the wavelength is located in the L-band, where the components are shipping in low volume. The cost is higher but shared by the users. There are three options for the upstream wavelength band. These options rely on transmitter's capability of controlling its wavelength. The wide band option (1524–1544) requires distributed feedback laser (DFB). As a result of the cyclic pass bands of the OLT demultiplexer, the DFB is able to “drift in wavelength over a wide range”. The second option is the narrow band option (1532–1540). This option can be applied by temperature controlled laser that is able to pick up a specified wavelength (Nesset, 2015). The last option is the reduced band (i.e. 1528–1540 nm).PtP WDM is assigned with two wavelength band options: The first one is shared spectrum. This option is applicable when considering “full co-existing scenario with legacy PON systems”. The second option is the expanded spectrum. This option utilizes the unused bands in a particular deployment to be assigned to PtP WDM. This option is usable for a Greenfield scenario (Nesset, 2015).

Table 6
NG-PON2 Wavelength band (ITU-T, G.989.1, 2014).

TWDM-PON		PtP WDM PON Upstream/downstream
Upstream	Wide band option (1524–1544 nm)	Expanded spectrum (1524–1625 nm)
	Reduced band option (1528–1540 nm)	Shared spectrum (1603–1625 nm)
	Narrow band option (1532–1540 nm)	
Downstream	1596–1603 nm	

6.2. *Spectral flexibility*

Spectral flexibility is one of the important features offered by NG-PON2. It refers to the ability of PtP WDM to use the un-used subset of optical spectrum that belong to TWDM or/and to legacy PONs. This feature allows the system to support different types of customer over the same ODN. Furthermore, spectral flexibility allows “a range of system coexistence scenarios and allows operators to” add new wavelength bands when legacy systems are decommissioned.” (Nesset, 2015)

6.3. *Co-existence*

NG-PON2 network utilizes wavelength in such a way that it allows every system to be processed independently over a shared infrastructure (Nesset, 2015). This allows co-existence with G-PON, XG-PON and RF video. Figs. 13 and 14 present NG-PON2 wavelength plan along with wavelength plan of G-PON, XG-PON1, and RF video for downstream and upstream respectively. The downstream channels of TWDM-PON are assigned between the wavelength bands of X-GPON1 downstream and the monitoring. Where the upstream channels defined in the C-band are “above the co-existence wavelength multiplexer edge at 1524 nm and below the 1550 nm RF video band”.

As shown in the figure, the wavelength band of PtP WDM is a combination of upstream and downstream plan that is defined based on the network operator requirements. Co-existence of PtP WDM with RF video is enabled by the wavelength plan; however, methods to compensate are needed (Nesset, 2015).

6.4. *ODN re-use*

One of the important demands of the network operators is the ability to re-use the deployed PON infrastructure in NG-PON2. Thus, NG-PON2 Physical media dependent (PMD) layer has been designed to be compatible with the component in ODN including power splitters and transceivers.

Additionally, to allow co-existence, nomenclature and values of optical path loss classes of NG-PON2 standard are required to be the same as XG-PON1 (Nesset, 2015). With respect to Greenfield scenario, several options of ODNs components are available for NG-PON2. The options include power splitter, and/or wavelength

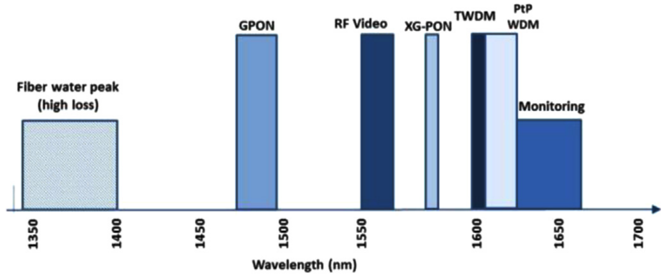


Fig. 13. Wavelengths plan for downstream.

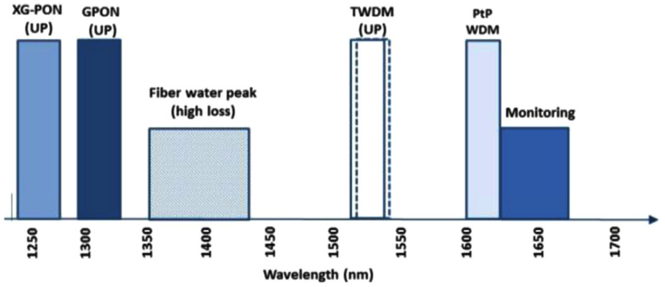


Fig. 14. Wavelengths plan for upstream.

splitter. However, splitting based on wavelength provides lower splitting loss and consequently extend the reach. Additionally, with the use of wavelength channels, wavelength splitting allows virtual private line services, which makes it more attractive (Nesset, 2015).

6.5. *Pay as you grow*

NG-PON2 is required to support pay as you grow applications. This means, the wavelength channels are added to the system one by one. Where the ONUs are colorless, they should be able to operate at any NG-PON2 channel. Furthermore, new services can be offered by adding a new channel (Nesset, 2015).

6.6. *Additional components*

For the sake of coexistence, there are a number of additional components need to be implemented at the ONUs and the OLT to perform the desired wavelength tuning functions (Murano, 2014; ITU-T, G.989.1, 2014).

For ONUs, a tunable receivers and tunable transmitters should be deployed to be able to selectively transmit/receive upstream/downstream channels. This can be obtained by using existing technology (Murano, 2014). The technologies available for the tunable transmitter include; tuned DFB laser with heating only control, tuned DFB laser with heating and cooling control, and the multi-section distributed bragg reflector (DBR) laser with/without cooling control (Nesset, 2015). The tunable transmitter could be un-calibrated, where the alignment of the wavelength is based on the OLT's feedback. This option cut the manufacturing costs.

With regards to tunable receiver, a number of components are available, but they are not mature as good as the tunable transmitter products. Few of the example receivers are the thermally tuned Fabry–Perot cavity filter, angle-tuned Fabry–Perot cavities, current injection-tuned silicon ring resonators, and liquid crystal filters" (Nesset, 2015).

At the OLT, the development and specification of the optical components have been concentrating mainly on the wavelength multiplexer and demultiplexer. A number of specific requirements are required in NG-PON2 device that are;

- ONU TTx control loop: to provide ONU with tuning feedback from the OLT.
- Wavelength multiplexer must work to combine the downstream signal and the demultiplexer must separate the signal more efficiently (Murano, 2014).

7. Precents implementation of TWDM

TWDM-PON has been receiving significant attention and many proposals have been submitted to evaluate its performance. In this section, the most widely accepted contributions during the last three years are reviewed and summarized in Table 7.

In (Zhengxuan et al., 2013), a symmetric TWDM-PON architecture is presented that can support 40 Gbps. This was achieved via stacking four wavelengths, each with symmetric 10 Gbps data rate in the upstream and downstream directions. In this technique, a directly modulated laser (DML) employed as an upstream laser source and a RSOA is installed at the ONUs to improve the sensitivity in the downstream signal. Additionally, a tunable optical filter is required at every ONU to manage the upstream chirp and to select the downstream wavelength. The simulation results show that with a 1:256 splitting ratio and a 25 km feeder fiber, the system obtains a power budget of 31 dB. A similar approach is presented in (Yi et al., 2013). However, the chirp management filter is implemented at the OLT rather than ONU. Consequently, the system produces a higher power budget (39-dB).

In (Li et al., 2014), the authors demonstrate a symmetric 40-Gb/s TWDM-PON. In this demonstration, 2048 users are supported over 40-km fiber with 51-dB loss budget. This has been achieved by utilizing SOA at the ONU to boost the upstream signal and consequently increases the external modulated laser (EML) output power. At the same time, pre-amplifiers boost the downstream signals to improve the sensitivity. Additionally, EDFA is implemented at the OLT to pre-amplify the received signal and consequently improve the upstream link loss budget. At the downstream, DML is employed as the laser source due to its ability to provide a high launch power (+16 dB per channel). The SOA at the ONU works simultaneously to pre-amplify the signal before being detected, which leads to improved sensitivity at the downstream link.

In (Bi et al., 2014), another demonstration of a symmetric 40 Gbps TWDM-PON based on DML transmitter in the downstream and upstream is presented. At the OLT, single bi-pass delay interferometer (DI) is implemented. The main function of DI is to mitigate multi-channel signal distortion imposed by laser chirp and fiber chromatic dispersion. Additionally, every transmitter and receiver at the OLT is equipped with an effective DFB laser. The

Table 7
Precents implementation of TWDM-PON.

References	Data rate	Implemented component at ONU/OLT	Splitting number of user	Distance	Power budget
(Zhengxuan et al., 2013)	Symmetric 40 G	DML RSOA	1:256	25 km	31 dB
(Yi et al., 2013)	Symmetric 40 G	DML RSOA	1:1000	25 km	39 dB
(Li et al., 2014)	Symmetric 40 G	EML & SOA DML- EDEA	2048 users	40	51 dB
(Bi et al., 2014)	Symmetric 40 G	DML &DI DML & DFB	1: 1024 1:256 1:46	50 km 75 km 100 km	43 dB
(Guo et al., 2014)	Symmetric 40 G	DML DFB EDC & EML	–	40 km	–
(Prat et al., 2014)	320 Gbps	RSOA A&D filter at RN	32 wave-length each with 1:32	100 km	35 dB
(Zhou et al., 2015)	symmetric 100-Gb/s	DML & NRZ DI	1:1024	25 km	42 dB
(Guo et al., 2014)	symmetric 100-Gb/s	RSOA & DSB OFDM OA	–	26.7 km	–
(Cheng et al., 2014)	40/10 Gbps	RSOA & DBR laser with external modulation EML	1:64	20 km	36 dB

system was tested for different range, which showed error free transmission with improvement in the power budget more than 43-dB.

In (Guo et al., 2014), a 40 Gbps transmission of symmetric TWDM-PON is demonstrated. The system has used four symmetric 10 Gbps data transmission using the wavelength bands defined in NG-PON2 (C band for upstream and L band for downstream) over 40 km. The transmitters at the ONUs implement a burst mode 10G DML. The OLT receiver and the electronic dispersion compensation (EDC) control the upstream dispersion penalty. For the downstream channel, the OLT transmitter was equipped with EML and the ONU was equipped with a tunable receiver. The demonstration results show that ODNs can attain satisfactory performance.

In (Prat et al., 2014), a successful test bed demonstration of TWDM-PON is presented. The distribution network is based on WDM bidirectional ring and the access network is based on TDM trees. The WDM ring supports 32 channels. The ring and the trees are connected using optical passive Add and Drop at RNs (32 RNs). Each RN has a specified wavelength. The RN amplifies the signal in the drop direction to the tree where it distributes to the ONUs. This configuration of TWDM-PON able to support more than 1000 users over 100 km range at 10 Gbps/100 Mbps–1 Gbps per user. One of the important features of the mixed topology is, it utilizes the ODN infrastructure optimally and provides scalability for the joining RNs.

In (Zhou et al., 2015), a new TWDM-PON architecture is presented that can support symmetric 100 Gb/s data rate. In this system, four pairs of wavelength spaced 100 GHz from each other are used for the downstream and upstream transmission. Each of the wavelengths is modulated by 25 Gb/s NRZ signals and stacked in both directions. At the OLT, DI realizes the frequency chirp for both the downstream and the upstream signals. The demonstration was conducted over 25 km range and showed successful transmission of the signals with 42 dB power budget.

Another symmetric 100 Gbps TWDM-PON architecture is proposed in (Guo et al., 2014). The system is based on four pairs of wavelengths each carries 25 Gbps of data. The demonstration is conducted over a distance of 26.7 km and employed a double sideband (DSB) orthogonal frequency division multiplexing (OFDM) modulation. At the ONU side, an RSOA is implemented to improve the sensitivity of the OFDM downstream signal. Additionally, SCFDE modulation is used at the ONU for upstream transmission to reduce the cost and complexity.

The presented TWDM PON system in (Cheng et al., 2014) supports pay as you grow application. This work allows smooth bandwidth upgrade and load balancing within one and different ODN by using flexible lambda connections and fast tunable transmitters. Furthermore, significant power saving at OLT has been achieved by supporting selective OLT with 100 GHz wavelength tuning in the OLT transceiver. This system is cost-effective as it integrates OLT transceiver with CFP and low cost tunable ONU transceiver with SFP+ module. The test-bed experiment shows error free performance for more than 36 dB signal strength. The performance of the network shows 2.3 Gb/s throughput in the upstream and 1.0 Gbps throughput per ONU in the downstream direction.

In (Yang et al., 2014), a mechanism to re-locate the wavelengths in TWDM-PON is proposed. The mechanism is based on sharing a pool of wavelengths and transceivers among connected TWDM-PONs. By taking into consideration the variations in traffic demand distribution for one PON and between multiple PONs during the day. It is possible to reduce the number of the working wavelengths and transceivers using the reallocation algorithm. The authors claimed that the number of wavelengths and transceivers can be reduced by 30% in comparison with conventional PON. In addition, the proposed algorithm reduces power consumption and cut the deployment cost at the OLT.

In (Chengjun et al., 2014), a management framework has been proposed. The framework saves energy, bandwidth, and time needed to migrate ONUs from the typical wavelength pairs to the new pairs. The framework is based on implementing a 1G transmitter at the OLT side to transmit control messages. The control signal is separated from the downstream signal by circucter CWDM. At the ONU side, two receivers are installed which are; 10G tunable receiver and 1G fixed receiver. The fixed receiver is always turned on to receive control messages. Where, the tunable receiver is turned on only during the allocated window time. It is powered off otherwise, consequently, reduces energy consumption.

The process of registration of new ONU is perform by broadcasting GATE message on the control channel. Where a dedicates wavelength pair is assigned for ONU registration. The new ONUs receive the message and turn their transmitter to the wavelength assigned for registration.

For migration mechanism, the OLT forwards migration commands to particular ONUs informing them to tune their transceiver to the new wavelength pair.

In (Sung et al., 2014), a new scalable TWDM-PON is introduced. In this scheme, the downstream receiver represented by tunable silicon-micro-ring (SMR) and ermanium-on-silicon photodiode (PD) Ge-Si PD. The main functions for SMR are to select the desired downstream wavelength and to demodulate the downstream DPSK signal. The Ge–Si PD works to detect the downstream signal. The upstream signal is produced by reflective-semiconductor-optical amplifier (RSOA) ring laser using OFDM signal. The scalability of this architecture presented by its ability to stack more than four transceivers into TWDM-PON utilizing cascaded SMRs.

8. XDM/WDM hybrid technologies

8.1. OCDM/WDM-PON

The combination of WDM and OCDM introduces advantages to the network including asynchronous multiplexing, high transmission speed, simplifying the management of the network, supporting a large number of users up to 3000 , reduction in the cost, expand coverage up to 100 km and improvement in the security. Another advantage of OCDM/WDM-PON technology is that it reduces circuitry by eliminating the need of encoder and decoder at each ONU. As it requires just one pair of encoder/decoder at ONU and OLT sides (Choi et al., 2013; Zulai et al., 2015).

OCDM/WDM-PON was proposed as a system that offers symmetric transmission in PON. Fig. 15 shows the basic architecture of OCDM/WDM-PON, which works by superposing OCDM channels over WDM channels. With every WDM grid (1–N), M users could be added using various optical codes. Thus, the total number of users in the network will be $N \times M$. The bandwidth offered by one wavelength can be shared between M users and every code in each wavelength can be repeated (Hernandez et al., 2012). However, implementation of such a system would need to upgrade all ONUs (Kramer et al., 2012), generate cost-effective optical orthogonal code, manage MAI and reduce the spectral due to increment in the network capacity (Hernandez et al., 2012).

In (Hou and Yang, 2014), a new architecture of OCDM/WDM-PON has been presented based on Differential Quadrature Phase-shift Keying (DQPSK). Few advantages of the DQPSK method are large dispersion tolerance, PMD and nonlinearity tolerance, high spectral efficiency, narrower spectrum width, and strong crosstalk-resistant capability. The proposed system shows less complex

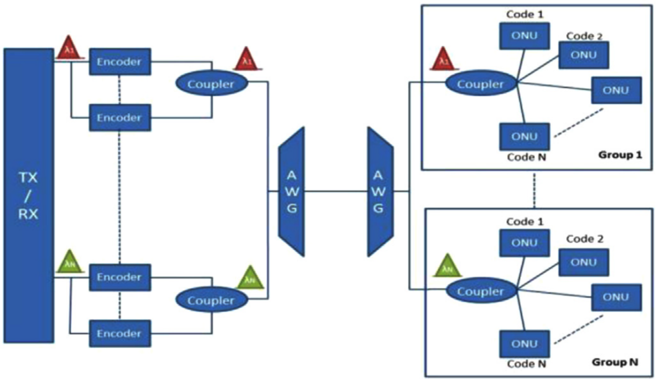


Fig. 15. OCDM/WDM-PON.

integration process, reduced number of decoder and encoder, smooth upgrade, and seamless integration.

Despite the advantages, the OCDM shows few drawbacks that are, with high traffic behavior it does not produce high energy efficiency results and consequences include more power consumption and high transmitted power. In (Zulai et al., 2015), authors present a mechanism to improve the energy efficiency of OCDM/WDM-PON. This mechanism is based on combining the sleep mode power-saving scheme and optimizations of the transceiver transmit power. The power saving scheme uses fast sleep or cycle sleep (which discussed in Section 11.3) technique. The power optimization uses relays on PSO-based power control algorithm. This helps to obtain an optimal SNIR by establishing the lower (optimal) transmitted power in each ONU according to maximum BER requirements. Additionally, the power control has ability to mitigate the effect of MAI imposed by changing transmitted power and number of active ONUs. The aim of the mechanism is to adjust the ideal transmitted power for each active ONU based on the DBA cycle. The analysis shows that this mechanism saves 75% of the energy. The proposed joint method is also capable of dealing with variation in traffic.

Reach-extended OCDM/WDM-PON proposed in (Choi et al., 2014) assigns C and L bands to uplink and downlink signals respectively. Broadband pulse source is used at the CO. The signal from this source is amplified and the spectrum is sliced at the RN. Splitter is used to split the sliced signal and then it is forwarded to the ONUs. For uplink transmission, the sliced signal is forwarded to RSOA. After amplification at RSOA, encoding is performed on the modulated signal. Then encoded signal is sent to the CO. The proposed system used FBG based N-chip fourier en/decoder. The experimental setup for the proposed system able to show 60 km of transmission range. The setup also able to produce 8 wavelengths by slicing 6.5 nm bandwidth. The number of ONU's can be increased by using special fiber with wider bandwidth. This will also reduce the transmission cost.

8.2. OFDM/WDM-PON

In OFDM/WDM-PON configuration, a group of OFDM subcarriers are transmitted over a group of wavelengths to different users as shown in Fig. 16. OFDM/WDM-PON is able to increase the capacity of the system up to few Tbps over a long distance providing services for multiple users and offering an efficient use of the bandwidth. In such a system, the generated OFDM subcarriers are modulated optically using a continuous wave (CW). In downstream transmission, all the wavelengths are multiplexed and transmitted through the fiber. A Local Exchange (LE) is needed in order to route and amplify the signals. At the ONUs side, every ONU is tuned to a wavelength, and an OFDM subcarrier. In the upstream transmission, the OFDM subcarrier is tuned to the upstream wavelength. All the wavelengths are integrated and amplified at the LE and transmitted to the OLT (Hernandez et al., 2012).

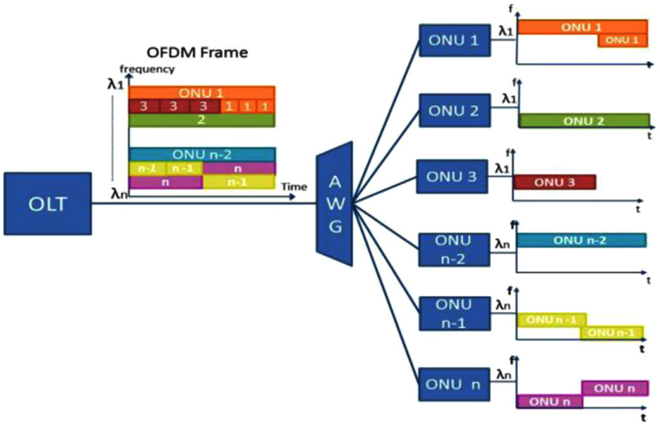


Fig. 16. OFDM/WDM-PON.

The challenges in implementing OFDM/WDM-PON are the need for advanced digital signal processing at the transceivers, a high speed converter (Analog to Digital/Digital to Analog), and a fast radio frequency (Muciaccia et al., 2014).

The bidirectional hybrid OFDM/WDM-PON presented in (Dong et al., 2012) has advantages of high bit rate, high spectral efficiency, low effect of RB, and power fading. For downlink, the system uses single side band OFDM. Whereas, for uplink transmission RSOA re-modulation is used. Another approach presented in (Vujicic et al., 2013), describes the experimental results of compatible single side-band (SSB) based technique by using mode locked combo source. After 50 km, the penalty of <1 dB was obtained at BER of $3x10^{-3}$.The performance of this technology can be enhanced by decreasing the tunable mode-locked laser (TMLL) free spectral range (FSR).

Stacked WDM/OFDM-PON can also be used to achieve 30.4 dB power budget to support 1:256 split ratio and 25 km range. In the proposed architecture, tuneable band pass filter was used for the selection of downstream and upstream. In OLT, outputs of four DFB lasers are fed into Mach-Zehnder Modulator (MZM) operated by OFDM signals (Vujicic et al., 2013).

9. XDM/TDM hybrid technologies

9.1. OCDM/TDM-PON

OCDM/TDM-PON is a scalable technology that allows multiplexing time intervals over multiple optical codes over a single channel without losing the original line bit rate. OCDM/TDM-PON is able to increase the system capacity up to $N \times 10$ Gbps. However, such a system requires additional equipment including one multiport OCDMA encoder/decoder (Yoshima et al., 2013) at the OLT and a Super-Structured Fiber Bragg grating SSFBG at every ONU. However, the main drawback of such a configuration is the difficulty of detecting the upstream burst signals (Kodama et al., 2013; Yoshima et al., 2010).

In (Kitayama et al., 2006), a demonstration of OCDM/TDM-PON has been presented focusing on reducing the crosstalk issues neighboring WDM using SSFBG encoder/decoder. This study shows that the crosstalk crosstalk can be negligible with intervals of 200 and 400 GHz. In (Kodama et al., 2013) a long reach with 65 km 10G OCDM/TDM-PON has been proposed. The architecture is based on implementing a pair of multi-Port encoder and decoder at the OLT and at the RN instead of t implementing encoder/decoder at each ONU. The extended reach is achieved by tailoring optical spectrum using narrow band optical band pass filter NB-OBPF. The demonstration shows a successful transmission without dispersion compensator.

9.2. OFDM/TDM-PON

OFDM/TDM-PON is another approach that can be considered for NG-PON2. This approach works by dividing each OFDM subcarrier among several services or users for each time slots (Kramer et al., 2012).

In (Cevik, 2013), the author proposes a new architecture that is based on OFDM/TDM for EPONs. This architecture eliminates the delay results from bandwidth allocation process (by sending and receiving the control messages) in the centralized scheme. The architecture is decentralized where the OLT will not be responsible for allocating bandwidth rather each ONU run a bandwidth demand determination algorithm. In this algorithm, each ONU reports its queue status to other ONUs through signaling channel. In a short time, each ONU will be aware of the load of the other ONUs. Accordingly, the load will be calculated and the bandwidth will be allocated dynamically for every cycle.

10. Hybrid XDM/TDM/WDM

Hybrid XDM/TDM/WDM is a possible approach that would enhance NG-PON2 performance. Technologies such as WDM/TDM/OFDM-PON and WDM/TDM/OCDM-PON have been presented in the literature and the nature of the possible hybrid combinations brings forth several advantages including greater dynamic bandwidth allocation flexibility, high scalability and extending the reach up to 100 km (Sotiropoulos et al., 2013; Kodama et al., 2013). The main drawback of this technique is its high cost.

In (Kodama et al., 2013), an experimental setup is established which consists of multi-port Encoder/Decoder. The feature of spectral periodicity of this Encoder/Decoder reduces the number of OCs required. The result of this experiment confirms that with the help of RS-FEC, the bit error rate of less than 10^{-3} can be achieved for the receiver sensitivity < -24.1 dbm.

11. NG-PON2 challenges

The NG-PON2 is to extend the coverage area, increase the bandwidth, increase the transmission speed, and save cost and energy (Bindhaiq et al., 2015). Despite the extensive research in developing NG-PON2 technologies, these factors still enforce challenges and remain under questions. In this section, these challenges are addressed and the recent developing progresses are discussed.

11.1. Increase the capacity

One of the most important challenges of NG-PON2 is offering a high bit rate (at least 40 Gbps downstream and 10 Gbps upstream), where each ONU is expected to support a data rate of 1 Gbps (Chanclou et al., 2012). Network capacity can be increased using one of the three techniques discussed below.

- Increase the number of wavelengths that are transmitted over the same fiber. This technique can be obtained by utilizing WDM and/or OFDM technologies that were discussed in the earlier sections.
- Increase the bit rate supported by each wavelength. This option can be achieved by using “larger signal constellations such as Dual Polarization Quadrature Amplitude Modulation (DP-MQAM) or Dual Polarization Modulation Quadrature Phase-Shift Keying (DP-MQPSK). Utilizing a modulation technique with a low Signal to Noise Ratio (SNR)” (Kataoka et al., 2010) improves performance; however, as a result of the nonlinear Shannon’s limit an increase in the data rate is also constrained. Additionally, this technique is considered expensive due to the use of the transponder that increases the cost by a factor of “2 or 2.5 with each fourfold increase in bit rate” (Kataoka et al., 2010).
- Nonlinearity compensation. The capacity of the fiber is restricted by the nonlinearities. “In the absence of noise, a single channel signal is limited by Self-Phase Modulation (SFM). Whilst, WDM systems are restricted by cross-phase modulation (XPM) as well as Four-Wave Mixing (FWM). The Nonlinear Schrodinger Equation (NLSE) is deterministic; this means that SPM, XPM, and FWM could be compensated with DSP” (Kataoka et al., 2010) techniques that might become practical as a result of the capacity improvement; consequently, the system strives to obtain the highest capacity achievable.

The approaches described are discussed in the literature as possible avenues that might lead to an increase in the network capacity. However, all of these approaches utilize advanced modulation formats. Modulation schemes being investigated include Quadrature Amplitude Modulation (QAM), Phase Modulation Quadrature Phase Shift Keying (PM-QPSK), Polarization multiplexing, and OFDM. Among these, PM-QPSK with a coherent receiver is the most popular modulation scheme in the industry (Hernandez et al., 2012; Alvizu et al., 2012).

11.2. Extend the reach

Extended reach is one of the requirements that next generation PON should feature (Mohamed and Ab-Rahman, 2015). LR-PON is a term that refers to the consolidation of the metro and the access networks (see Fig. 17) (Song et al., 2010). It aims to extend PON's domain up to 100 km. It reduces the number of active elements in the network, minimizes network planning efforts, and reduces the capital expenditure (CAPEX) and OPEX. Several techniques have been studied to realize this objective.

The first architecture for LR-PON was introduced by British Telecom. The major objective was to meet bandwidth demand and to integrate some of the COs across the country. This architecture allowed symmetric transmission of 10 Gbps over 100 km distance with a split ratio of 1024 (Shea and Mitchell, 2007). This system deployed six optical amplifiers for upstream and downstream transmission. In addition, an intermediate amplification unit was placed at the local exchange after the split. The idea behind implementing the intermediate amplification unit was to contain electrical power, therefore, there would be no need to install electrical power generators in the distribution section. Furthermore, the optical amplifiers were located after the spit which eliminated the need for parallel optical amplifiers. This also removed noise related issues (Shea and Mitchell, 2007).

Another LR-PON based on DWDM-TDM was proposed by Tail and Townsend. This LR-PON integrates a large number of users and attains extended reach by optically amplified PONs. This system offers symmetric transmission of 10 Gbps and supports 4352 users over 100 km range (Shea and Mitchell, 2007). DWDM is based on narrow optical filtering. As a result, the selection of the transmitter technology is crucial and a strict wavelength definition is required to separate individual channels (Talli and Townsend, 2005; Behzod and Adan, 2013).

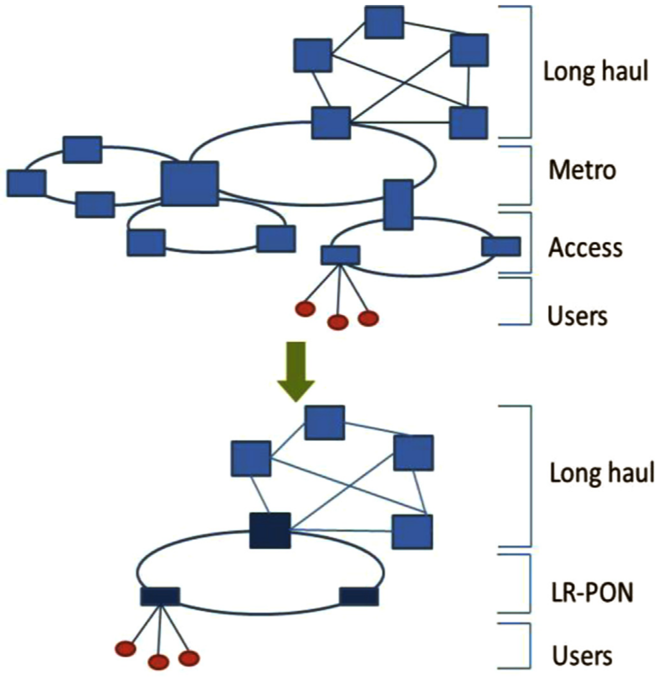


Fig. 17. LR-PON (Song et al., 2010).

The GPON system communication range has been extended up to 120 km by implementing a wavelength converter. This system has been demonstrated in (Shea and Mitchell, 2007), it supports up to 1280 users. Further extension up to 135 km has been achieved in (Davey et al., 2006). In this system, optical to electrical to optical OEO conversion is implemented. The function of OEO is to convert the burst mode GPON system into a DWDM system. The system prototype showed successful data transportation with a BER better than 10^{-10}.

LR-PON based on an OFDM signal is another potential technique. It offers high tolerance to chromatic dispersion and attains high spectral efficiency. The first demonstration of utilizing OFDM for signal demodulation in LR-PONs has been presented in (Chow et al., 2009). The study involved different types of ONU over 100 km and achieved error free operations.

1) The most common practices to extend the reach of PON are discussed below (Wong, 2012; De Andrade et al., 2014) Optical amplification:
   The use of optical amplifiers is widespread and enables LR-PONs to achieve the target power distribution quotas. There are several types of optical amplifiers including, Erbium Doped Fiber Amplifier (EDFA), Semiconductor Optical Amplifiers (SOA), and Distributed Raman Amplification) (Wong, 2012; Skubic et al., 2010).
   Although EDFA has a decent power saving rating as well as reasonable noise performance in C and L bands, its performance is limited only to these bands (Wang and Chang, 2015), which makes it unsuitable to cope with the burst of an upstream transmission.
   A key advantage of SOA is the ability to operate at any wavelength band including the O band (1310 nm), C band (1550 nm), and S band (1490 nm). Furthermore, comparing to EDFA, SOA has better gain dynamics. Additionally, it simplifies some functions including wavelength conversion and all-optical regeneration. However, it executes on a per wavelength basis that leads to a limitation on offering simultaneous amplification across multiple wavelengths (Wong, 2012).
   DRA supports amplification over a wide channel area over a bidirectional link. Such amplifiers offer a flat optical gain bandwidth including channels that override those of common optical amplifiers (Wong, 2012).
2) Electronic Repeater-Based Networks:
   Using an Electrical Repeater at a local exchange is another option for optical amplification with a high split ratio. It brings a number of benefits including the 1R (retransmission) or 2R (re-time and re-transmit) regeneration of downstream and upstream signals, “wavelength conversion and equalization in optical power of the upstream burst mode signals”. On the other hand, electronic repeaters require a bit-rate specific burst mode receiver that must possess a wide dynamic range (Wong, 2012).
3) Purely Passive LR-PON:
   With optical amplification and an electronic repeater it is necessary to provide power in the local exchange, this eliminates one aspect of the passive nature of the network. An alternative option is to keep the distribution network purely passive by using developed modulation formats as well as digital coherent detection (Wang and Chang, 2015). Extending the reach creates serious challenges for the MAC layer. As the reach is extended, the round trip time (RTT) grows. When the DBA performance for the PON relies on the RTT, there is an impact on the delay of the DBA control loop. The growth in RTT leads to a performance decrease (Skubic et al., 2010). Even though LR-PON is a significant approach that would extend PON networks and to reduce overall cost, there remain a number of limitations that include large propagation delays and this leads to inefficient utilization of upstream channels (De Andrade et al., 2014).

11.3. Power saving

The recent progress in PON technologies includes an effective development in power saving functions. According to ITU-T series-G supplement 45 “G-PON power conservation”, four approaches for ONUs' power saving have been put forward. These approaches include;

1) *Power shedding:* Power shedding method is performed by the ONU. It switches off certain services to reduce the consumption of the power during AC power failure (Kim et al., 2014).
2) Dozing: This approach works by setting the transmitting function of ONU into sleep state while the receiving function into wake state. In TDMA-PON, inherently, the process of upstream transmission is considered energy efficient, where the ONU will be active if it has data to transmit. The purpose of implementing dozing technique is to put the laser drive as well as the electrical functions at the transmitter into sleep mode and suspending laser emissions. In a typical PON, the ONU requires to send a grant request messages during each TDMA cycle either it has data to transmit or not. However, in dozing method, the ONU does not send the grant message if it does not have traffic (Kani et al., 2013).
3) Deep sleep: In this approach, the transmitting and receiving functions are in sleep state. To wake up the ONU, a negotiation with OLT is required. Although this technique shows huge saving in the power than the dozing, the possibility of losing the downstream data increases (Kani et al., 2013).
4) Cyclic sleep:
   Cyclic sleep is an efficient technique. It overcomes the issue of losing the downstream data in the deep sleep approach. It works by pushing the transmitting and receiving functions in the sleep state while the indented ONU has no traffic to transmit. However, the functions will wake up periodically to capture any downstream data (Kani et al., 2013).

There are many scope of power saving in the ONUs compared to the scopes available in the OLT. Beside the approaches discussed above, a number of novel approaches have been investigated lately (Vetter et al., 2014; Zulai et al., 2015). These approaches include;

- Very fast sleep control: In this approach, the OLT is responsible for determining the start and the end period of sleeping. During the sleep period, the ONU will not receive downstream or control signals (Skubic et al., 2012).
- Optimization of traffic flow and scheduling: his approach maximizes the sleep time by scheduling the time of the downstream and upstream traffic for each ONU (Skubic et al., 2012).
- Bit interleaving: in this method, the downstream signals are multiplexed bit by bit instead of frame by frame. A substantial power savings is achieved in this method as a result of a small portion of the entire bit rate is intended to a specific ONU (Skubic et al., 2012).

Although, these approaches show a significant power saving, they are not standardized yet (Skubic et al., 2012). For NG-PON2, the power saving is still a challenging task. In (Kani et al., 2013), two scenarios have been defined to decrease the power consumption of the NG-PON2 networks. The first scenario is based on construction of a Point to Point (P2P) or Virtual P2P optical access system. This includes WDM-PON. The concentration of the electrical process is carried in the aggregators. Where, the aggregator saves substantial amount of power when applying current technologies. The other scenario is based on engaging the Ethernet aggregator function into the access network. This includes approaches such as: High-speed and high split TDMA-PON and Dynamic TWDM-PON and wavelength routing. The later approach has been discussed in (Behzod and Adan, 2013), where the authors developed a simple algorithm that realizes optimal power saving.

12. PON reliability aspects

12.1. PON protection mechanisms

One of the most important features required in NG-PON2 is offering a high reliability performance. NG-PON2 supports longer reach leading to encounter high probability of fiber cut. Thus, ensuring the system reliability by implementing protection mechanisms is essential requirement.

According to ITU-T G.983.1, four types of protection configurations are defined (ITU-T, 2005).

- Type A: protect the feeder fiber only
- Type B: protect the feeder fiber and the OLT
- Type C: protect all components
- Type D: protect the feeder fiber and the branch fiber.

As NG-PON2 supports different user's profile, the level of protection is varying. Business users need to have fully protected networks. Usually, “there is a service level agreement (SLA) between” the network providers and the business users. The network providers are required to pay for service interruptions. This level of protection increases the cost significantly. In contrary, the residential users are seeking for low cost services. As a result, it is very important for NG-PON2 to provide protection with different degrees of resilience based on the user's profile (Dixit et al., 2014).

In (Dixit et al., 2014; Mahloo et al., 2014; Kaneko et al., 2015, 2014), several studies have been conducted to design methods and architectures to improve reliability of NG-PON 2.

12.2. PON security

Any communication network that transmitting confidential and sensitive information is required to follow rules to guarantee safety and security of transmission.

The security functions for such network are defined in Standard ISO 7498-2 ISO / OSI Security Architecture. These functions are performed at the different layers of the reference model. The security functions are classified into following five groups:

- Authentication services
- Access control services
- Confidentiality services
- Integrity services
- Non-repudiation services

Among these functions, confidentiality and authentication services are the most important functions to be considering in PONs (Koudelka et al., 2015).

In TDM-PON, the security threat is higher in the downstream transmission, where any ONU can eavesdrop on the other downstream traffic. The eavesdropping issue in the downstream traffic has been recognized by implementing 128-bit AES encryption in ITU-T and IEEE standards. In addition, XG-PON supports enhanced security by encrypting unicast and multicast traffic. Even though PONs support this security feature, eliminating eavesdropping issue cannot be guaranteed. For example, there is possibility of eavesdropping at the upstream traffic during the process of registration of new ONU. At this stage the eavesdropper can generate the system keys. WDM-PON creates P2P connection at the physical layer, therefore eavesdropping issue is eliminated. However, with the use of AWG, the security risk appears with the crosstalk between the channels (Fröhlich et al., 2015). Many emerging applications of PON such as smart power distribution systems (Smart Grid) or telemedicine (eHealth) demand better protection of PON traffic.

12.3. PON monitoring

Considering the big amount of traffic that travel over PON, a cost effective and reliable management system is highly desired. It is evident that any fault in the fiber feeder will result in the network failure. This leads to big investment loss for the service providers. Fixing fault requires determining the faulty section in the network, then locate the exact location of the fault, and finally send the technicians to repair the fault. According to Federal Communications Commission (FCC), one third of service disturbance is because of cable issues. Therefore, fast detection and managing the fault is an important requirement in such network configuration. Physical layer monitoring is an important to guarantee the reliability of the network, this leads to define ITU-T L.66 (2007) recommendation. Where, the U-band with wavelength between 1625 and 1675 nm have been granted for PON maintenance (Esmail and Fathallah, 2013).

The monitoring techniques of PON can be classified into Optical Time Domain Reflectometer (OTDR) based and non OTDR based. The OTDR is an efficient tool to determine and locate the exact location of the fault. It works by injecting a test pulse into the fiber cable and measures the backward signals. A trace is presented by computing the power versus the distance where several information about the link status can be extracted including bends, mismatch, misalignment, fiber break and others (Esmail and Fathallah, 2013; Rad et al., 2011).

However, traditional OTDR cannot be implemented with PON for several reasons. Firstly, PON is a point to multi point architecture, where the reflected signal will be a linear sum of all

Table 8
Monitoring techniques.

	Monitoring technique	Cost	Capacity	Scalability	Complexity	Reliability	Transparently	Centralized	Automatic
Single Wavelength OTDR	Upstream OTDR	High	Low	No	Low	Low	No	No	No
	Active bypass	Low	High	No	Low	Low	Yes	Yes	Yes
	Semi-passive bypass	Low	High	No	Low	Low	Yes	Yes	Yes
	Reference reflector	Low	High	No	Low	Low	Yes	Yes	Yes
	Switchable reflective element	High	High	Yes	Medium	Low	Yes	Yes	Yes
Tunable OTDR	Wavelength routing	High	Low	No	High	High	Yes	Yes	Yes
	Reference reflector	High	Low	No	Medium	High	Yes	Yes	Yes
Brillouin OTDR		High	High	No	Medium	Medium	Yes	Yes	Yes
Embedded OTDR		Medium	High	Yes	High	Low	No	No	Yes
OFDR+IF units		Low	High	Yes	Low	Medium	Yes	Yes	Yes
Optical coding		Low	High	Yes	Low	Medium	Yes	Yes	Yes
SL-RSOA		Low	High	Yes	Medium	Low	Yes	No	Yes
Reflected signal		High	High	Yes	Low	Medium	Yes	Yes	Yes

backward signals which make it difficult to distinguish between the backwards signals coming from multiple branches (Rad et al., 2011; Esmail and Fathallah, 2013). Secondly, connection point in the fiber lines and the short range in between them makes it difficult to implement OTDR (Esmail and Fathallah, 2013). In addition, with increasing network size, OTDR becomes more unreliable (Rad et al., 2011). Detecting the fault needs high dynamic range (DR) at the OTDR which is difficult due to the use of splitter which has more than 21 dB loss in power (Esmail and Fathallah, 2013).

Several solutions based on modified OTDR can be found in today's market. However, they still suffer from define and locate the fault minutely problem. In (Esmail and Fathallah, 2013), an extensive review of several existing solutions in the market to manage the fault for PON at the physical layer is presented. Table 8, summarises these techniques based on the required features of the monitoring system (Rad et al., 2011). Different Non OTDR based techniques have been introduced. Brillouin Frequency Shift Assignment (BFSA) and Optical Coding (OC) are among the mostly demonstrated techniques. BFSA offers each fiber branch located beyond the RN with a unique OTDR trace. This technique brings some difficulties in designing the network infrastructure. The identification fiber (fiber from the RN to ONUs that distinguished by a specific Brillouin frequency shift) needs to be manufactured with several physical characteristics in order to produce and return various Brillouin frequencies. In addition, the identification fiber needs operate at the data link to fulfill the data transmission requirement of the PON. Moreover, it is required to design a new fiber and replace the current distribution fiber. This leads to increase in cost and as the network capacity increase the cost also increase. Thus, commercially such technique is undesirable. The OC technique is receiving research interest as it increases the scalability, and significantly reduces the complexity and the cost. However, a complete fault localization feature is still missing (Rad et al., 2011). In this technique the test signals are transmitted on a dedicated band (U band), where the data signals are transmitted on a different band (L-band). At the CO, an n-optical source transmits the downstream monitoring signals. The signals are splitted by the splitter to N subpulses equal to the number of the branches. Passive encoders are placed at the edge of the distribution fibers to identify each branch. The encoders work to encode the signal by a unique code and reflect the signal back to the CO. At the CO, the electronic receiver aggregates the upstream monitoring signal and the NMS make a decision about the status of the link.

13. Future aspects of PON

NG-PON2 has been utilized to develop many applications and services such as mobile services, fiber wireless convergence, cloud computing, and big data.

Mobile fronthaul (MFH) and mobile backhaul (MBH) are the two main technologies that provide 4G and 5G mobile services (Kani et al., 2015). The general architecture of NG-PON2 that supports mobile services is shown in Fig. 18. The NG-PON2 reuses the present network resources to cover all the fixed and mobile services by assigning a TWDM-PON to FTTH and FTTB while assigning PtP WDM channels to MBH (Iiyama et al., 2015).

There are ongoing researches for the candidate technologies of PON based mobile optical network technologies. Some of the technologies as follow (Taniguchi et al., 2014):

- Digital signal processing (DSP)-based Advanced Modulation formats for Co-existence PON Configuration (Iiyama et al., 2015; Taniguchi et al., 2014).
- Technologies for Effective Utilization of Optical Transmission Bandwidth (Shibata et al., 2013; Taniguchi et al., 2014).
- Low-latency Dynamic Bandwidth Allocation for TDM-PON based MFH (Tashiro et al., 2014; Taniguchi et al., 2014).

In (Breuer et al., 2015; Lee et al., 2014; Hussain et al., 2014), some of the most recent implementations of NG-PON2 architectures are presented that provide mobile services.

PON has been investigated to support wireless backhauling. With the development of NG-PON2, it is expected to increase the coverage and centrally connected base stations. Consequently, reduction in the cost of backhauling links (Thakur et al., 2014).

A number of projects and studies have investigated different techniques to allow wireless traffic over the optical network. Some of the studies carried out were (Mitchell, 2014):

- ACCORDANCE. In this project, the integration of wired and wireless standards is based on OFDMA-PON.
- FIVER. Two architectures were proposed to provide 3PLAY wireless services (LTE, Ultra-wideband, WiMAX):
  - CWDM FTTH architecture
  - Reflective FTTH architecture with R-EAT (Llorente et al., 2011)

- Building the Future Optical Network in Europe (BONE). This project supports a number of studies that aims to propose wireless/optical access network architectures (e.g. LTE and WiMAX services) (Milosavljevic et al., 2012).
- ISIS. A range of systems from UWB to WiMAX and 3G standards.

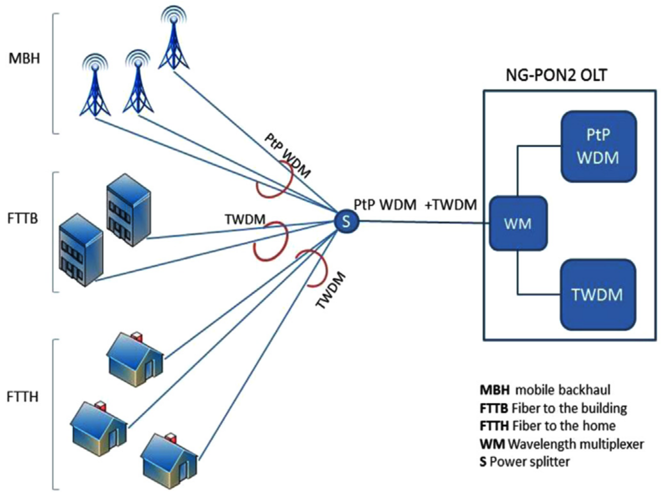


Fig. 18. NG-PON2 and mobile services.

- The European research project FUTON (Fiber Optic Networks for Distributed, Extendible, Heterogeneous Radio Architectures and Service Provisioning. An integrated optical access and wireless architecture has been proposed by using coordinated multipoint (CoMP) techniques (Diehm et al., 2010).
- e-Photon/One. In this project, traffics from 3G base stations are delivered over GPON.
- In (Chow et al., 2015), wireline and wireless/optical access network integrated architecture based on TWDM-PON has been demonstrated. This implementation utilizes bit-loading orthogonal frequency modulation to obtain a high data rate.

In addition, with the huge bandwidth that is being offered by NG-PON2, it would provide an ideal platform to support cloud computing and big data applications (Behzod and Adan, 2013).

14. Discussion and future works

This paper reviews the EPON and GPON standards in terms of the physical and data link layers. EPON has a simple layering model where it supports a native Ethernet frame to carry data, voice, and video. On the other hand GPON uses two layers of encapsulation which are the GEM and GTC to transport three frames that are Ethernet, ATM, and TDM; hence, layering and management become more complex. Furthermore, GPON equipment needs virtual channel, segmentation and reassembly, multiple protocol conversions, and point-to-point protocol. Whereas, in the EPON standard, all of the required devices are ubiquitous all the way to the backbone network which in turn makes EPON implementation cost effective.

Moving from the deployed PON to NG-PON1 that provides up to 10 Gbps bit rate includes three scenarios that are from EPON to XG-EPON, from GPON to XG-GPON, and from GPON to XG-EPON. Each scenario inherits features from the deployed PON and requires modifications in the physical layer to enable successful integration. However, further increases in the data bit will be required to cope with the rapid grow of high bandwidth applications. Thus, most of proposals found in the literature promote NG-PON2 because it offers a bit rate up to 100 Gbps. The proposals have generally included outcomes based on four major technologies including TDM, WDM, OCDM and OFDM.

TDM-PON is the simplest technology that utilizes the bandwidth effectively. However, it suffers from a capacity limitation where the bandwidth is shared among all of the users and each user is assigned to a certain time interval, which leads to reduced bandwidth per user. Furthermore, security is not guaranteed due to the fact that the downstream traffic is broadcast to all the users which lead to the possibility of eavesdropping and to overcome this limitation data encryption is required.

WDM-PON on the other hand eliminates the capacity limitation and security issues in TDM by assigning a wavelength to each user; thus, building a virtual point to point connection between the OLT and ONUs. Moreover, the individual wavelength for each user permits capacity upgrades without the need for additional infrastructure that might have an impact on the other users. However, inefficient bandwidth utilization may occur using this approach and the cost of implementing WDM-PON is higher than TDM-PON as it requires equipping additional devices such as AWG and colored ONUs. Solutions such as RSOAs, REAMs, optical modulators, and tunable lasers have been introduced to reduce the cost, but the cost still remains relatively high.

OCDM shows better performance than TDM and WDM in terms of bandwidth utilization and security. Improved bandwidth utilization is achieved by the asynchronous access feature, where the transmitted channels are allowed to overlap in time and frequency domains. Security is improved in the encoding and decoding process by carrying out actions in the optical domain and the receiver is restricted to decoding only traffic meant for it. However, MAI and Optical Beat Noise are two noise sources that appear as a result of supporting a large number of users and this leads to performance degradation.

OFDM-PON is another technology that offers advantages including dynamic subcarrier allocation, efficient spectrum utilization, 2-D bandwidth map and using inexpensive electronic devices to reduce overall costs. This technique has been successfully applied to WiMAX, WiFi, and UWB at a reasonable cost. A major challenge associated with upstream transmission in OFDM-PON is optical carrier de-correlation that results from the transmission of traffic from multiple ONUs to the OLT over a single wavelength and with differences in fiber length. Such mingling of photo-detection generates optical beating noise and makes transmission synchronization difficult to attain.

As shown in this paper, a number of open issues must be addressed to improve the development of the NG-PON2 technologies. These issues suggest a range of research guidelines that are required to be followed in order to improve NG-PON2 performance. As discussed previously, individual technologies have their own limitations; hence, the hybrid technologies have been introduced to improve performance. Although TWDM-PON has been considered as the most prominent solution that meets the next-generation requirements, experimental investigation of other hybrid technologies is needed to find out whether it is possible to achieve better performance. Hybrid technologies that include OCDM or/and OFDM based LR-PON are a key solution to overcome the major challenges of increasing network capacity and reach, and reducing the total cost and power consumption. Research is ongoing and applying the methods discussed previously might provide data rates of 100 Gbps and beyond. The use of OCDM or/and OFDM for LR-PON is an important research direction that could lead to improved long reach networks at reduced overall cost.

15. Conclusion

This paper provides a literature survey of research into potential approaches for next generation PON. The paper showcases the required modifications for each standard in terms of the physical layer. In addition, this review highlights the requirements and the multiplexing techniques for NG-PON2 and identifies the pros and cons. Furthermore, hybrid technologies that are being used to fulfill the requirements set for NG-PON2 are also discussed. Despite the work and the effort that have been invested to improve PON performance, challenges remain and should be explored in future studies.

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