Passive Optical Networks, Introduction

1. INTRODUCTION

In the last 30 years, there has been a fast-growth of multimedia streaming services such as Video-On-Demand (VOD), online gaming and high-definition television over the Internet that has been requiring new broadband access networks. In order to deal with that situation, traditional copper-based access networks, which are extremely widely used in many countries, have quickly been replaced by optical fiber-based access networks. After three decades of dynamic research, Passive Optical Network (PON) has been considered as the most promising broadband access solution for its wide bandwidth, low-cost deployment and maintenance.
The main objective of this work is to provide an overview of the state of the art of Passive Optical Networks as well as their basic concepts. This work is mainly divided into four sections. In Section 1, we give a summary of the main concepts of passive optical networks. Sections 2 and 3 introduce the most important features of ITU-T recommendations and IEEE standards for passive access networks, respectively. Finally, Section 4 concludes the work with an overview about the future trends of PONs for access networks.

1.1. First-Mile Concept

Generally, a modern telecommunication network is divided into three main segments as is depicted in Figure 1 [1]. The segments are backbone (or core) network which is used for long-distance transport, metro/regional network that is responsible for traffic grooming and multiplexing functions, and access network which provide end-user connectivity.
The access networks have been named last-mile networks. They comprise the last segment connection from service providers' Central Office (CO) to end users. Lately, they are also called first-mile networks because they are the first segment of the broader network seen by users of telecommunication services [1]. Depending on transmission medium used, access networks can be sorted into three categories: i) copper such as twisted pairs and coaxial cable, ii) wireless, and iii) fiber. These categories of access networks will be introduced in Sections 1.2 and 1.3, respectively.

1.2. Basic Technologies of Access Networks

Depending on the type of the transmission medium utilized, the basic technologies for access networks have been divided into three categories:
Copper-based networks. The first broadband access network standard known belongs to Digital Subscriber Line (DSL) technology family, and its name is Integrated Services Digital Network (ISDN). This standard offers 144kbps as maximum of transmission range in both downstream (carrier to user) and upstream (user to carrier) directions over a single twisted copper pair different to the one used in the traditional Plain Old Telephone Service (POTS) [2]. It is because the ISDN and POTS spectrums are overlapping. The POTS and ISDN work bands are 0-4 kHz and 0-50 kHz, respectively. Due to the high cost, the ISDN services have never been popular. Thus, others flavors of DSL technologies (commonly called xDSL) have been designed for broadband data transmission over twisted pairs in order to satisfy the customer expectations [3], which include more and more multimedia data. DSL services make use of the higher frequency range on twisted pairs for data transmission. Usually, the upstream direction data is established between 25 kHz and 160 kHz and the downstream direction data from 240 kHz to 1.5 MHz [1]. The modulation technique most used in DSL is Discrete Multi-Tone modulation (DMT) [4, 7], which divides the frequency bands before mentioned into 247 channels of 4 kHz slots [1, 5]. Signal quality is degraded by copper wire quality, bridge taps on twisted pairs and cross talk between neighboring twisted pair. For this reason, the signal quality in each slot is constantly checked and the signals are moved from bad slots to good ones in an adaptive manner. However, DSL data rates and transmission distances are limited. Table 1 gives an overview of the different DSL technology performances [1, 6].

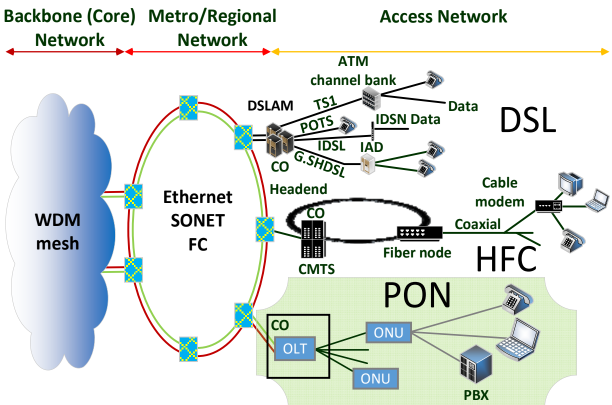


Figure 1. Generic structure of a modern Telecommunication network [1].

Cable Modem (CM)-based networks. This type of access networks, which is based on coaxial cable, arose from traditional CATV networks were the most popular one-way broadcast systems in the United States (US). In 1990, Multiple Service Operators (MSOs) began to reform their traditional one-way analog broadcast systems by putting in bidirectional RF amplifiers and return optical links in order to provide data and other services such as Video-On-Demand (VOD). The cable modem growth started in 1996 when the Telecom Act in the US liberalized the telecommunication service market [8]. Soon, this access network was the dominating form of broadband access in the US for two main reasons. Firstly, the coaxial CATV plant coverage is far more complete than in other countries. Hence, the majority of households are connected to MSO providers through coaxial cable drops. Secondly, the data over cable service interface specification

(DOCSIS) 1.0 released in 1997 made significant contribution to the success of cable modem by offering a common specification for multivendor interoperability and consequently helped to lower the equipment and service costs [9].

DSL type	Max Speed Upstream (Mbps)	Downstream (Mbps)	Reach (km)	POTS support
A	0.8	8	5.5	Yes
H	1.54	1.54	3.65	No
ISDN	0.144	0.144	10.7	No
M	2	2	8.8	No
RA	1	7	5.5	Yes
S	2.3	2.3	6.7	No
V	16	52	1.2	Yes

Table 1. Overview of the different DSL technology performances.

In a cable modem system, cable modems at individual households are connected to a Cable Modem Termination System (CMTS) at a headend office. The tree-and-branch coaxial cable plant forms a shared medium among the users in which customer data are multiplexed using the Time Division Multiplexing (TDM) scheme. In downstream direction, each individual cable modem recognizes its data by the ID embedded in downstream data. Cable modem upstream transmission is established between 0 and 45 MHz. This frequency range usually has poorer channel characteristics due to the coupling from sources such as home electrical gadgets. Another source of degradation in the upstream band is due to the noise funneling effect from all the upstream users [10].

Quadrature Amplitude Modulation (QAM) [11], which encodes multiple bits of information on each symbol, was proposed as modulation technique by DOCSIS. 64-QAM and 256-QAM are used for downstream modulation by DOCSIS 1.0. For upstream connections, 4-QAM and 16-QAM are used. DOCSIS 2.0 [9] increased the upstream capacity by employing 32, 64, and 128-QAM. DOCSIS 3.0 [9] further increased the available data bandwidth to above 100 Mbps in both directions through a technique called channel bonding. Table 2 shows an overview of the different DOCSIS version performances [1]. Different versions of the DOCSIS protocols have been made backward compatible.

DOCSIS version	Max Speed Upstream (Mbps)	Downstream (Mbps)
1.0	38	10
2.0	40	30
3.0	160	120

Table 2. Overview of the different DOCSIS version performances.

Wireless-based networks. This type of technology is characterized by the lowest deployment cost [12]. In the last years, the best known standard for wireless broadband access network has been Worldwide Interoperability for Microwave Access (WiMAX). WiMAX is the prevalent term for IEEE standard 802.16, which is named Air Interface for Fixed Broadband Wireless Access Systems [13]. The initial implementation, which is described in 802.16-2004, is being done by means of a fixed network of base stations but WiMAX is also proposed as mobile access network in 802.16e [14]. That is to say, WiMAX can support wireless transmissions directly to mobile end users.

For fixed access, WiMAX operates in a frequency band running from 2GHz to 11 GHz and the modulation technique used is Orthogonal Frequency-Division Multiplexing (OFDM) [15]. In this context, WiMAX has a useful range of about 50 km at a data rate of 70 Mbps over a channel of 20 MHz of bandwidth [12]. As mobile access network, Mobile WiMAX utilizes the spectrum that is extended from 2 GHz to 6 GHz and the employed modulation technique is Orthogonal Frequency-Division Multiple Access (OFDMA) [16], a multi-user version of OFDM. That technique is based on assigning subsets of subcarriers to individual user allowing simultaneous low-data-rate transmission from several users. In this way, the data rate per channel, each one typically of 5 MHz, is 15 Mbps for a maximum reach of 5 km. The Mobile WiMAX was designed to provide for fourth-generation (4G) services, beyond the horizon of the already well-established third-generation (3G) cellular networks such as Universal Mobile Telecommunications System (UMTS) [17]. UMTS was standardized by the third-generation partnership project (3GPP) [17, 18]. That project belongs to IMT-2000, the common name defined by ITU for 3G systems. The key idea of UMTS is to be as dynamic as possible and to use system resources for different purposes. Thus, the spectrum is divided into small channels of 5 MHz of bandwidth on which a maximum bit rate of 2 Mbps could be reached. The coverage of UMTS compare to Mobile WiMAX is higher, up to 35 km. Unlike Mobile WiMAX, UMTS uses code division multiple access (CDMA) [19]. Table 3 shows a comparative between Mobile WiMAX and UMTS.

Parameter	Mobile WiMAX	UMTS
Data Rate (Mbps)	15	2
Bandwidth (MHz)	5	5
Multiple Access Technique	OFDMA	CDMA
Division Duplexing	Time (TDD)	Frequency (FDD)
Mobility	Low	High
Coverage	Mid	Large
Standardization	802.16e	3GPP
Target Market	Home/Enterprise	Public

Table 3. Mobil access network technology comparative.

1.3. Access Network Based on Fiber

Optical fiber is characterized by high bandwidth, low loss, and low noise. Furthermore, fiber plants require very little maintenance. Studies for access network based on optical fiber started at the end of 1980s [20, 21]. Figure 2 shows the most common access networks based on optical fiber. Fiber access networks are also denoted as Fiber-To-The-X (FTTX) system, where X can usually be home (H), basement (B), premises (P) as a generic term for H and B, neighborhood (N), curb (C), and antenna (A) depending on how deep in the field fiber is deployed or how close it is to

the user.
FTTX systems can be Point-To-Point (P2P) or Point-To-Multi-Point (P2MP) and they can use an active Remote distribution Node (RN) such as an Ethernet switch or a passive RN such as a simple passive splitter or a WDM coupler. The most direct approach for FTTH (see Figure 2) is the P2P "home run" or single star around the central office. When fiber runs are long enough, a high-speed electronic multiplexer at the remote site is more economical than multiple fiber runs, thus forming an active double star with fiber to individual customer [22]. Passive Optical Network (PON), using passive optical multiplexing devices, save the cost of a terminal in the field at the potential added cost of more complicated terminals. Nowadays, PON is considered as a synonym of Fiber-To-The-X (FTTX). However, the FTTX model is broader than PON in which there are not active elements between the CO and customers' premises. It is for this reason that PON deployment and maintenance activities cost are lower.

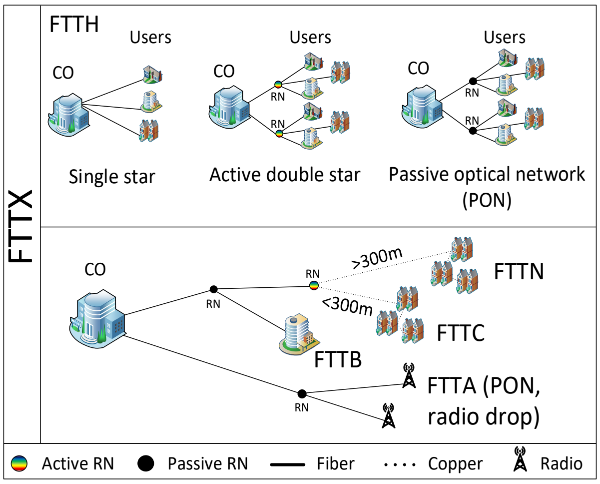


Figure 2. Fiber-based access networks [22]. FTTX: Fiber-To-The- Home (H)/Neighborhood (N)/Curb (C)/Antenna (A), CO: Central Office, RN: Remote Node.

1.4. Basic Passive Optical Network (PON) Architecture

Figure 3 shows the architecture of a typical PON wherein a fiber optic network connects switching equipment in the CO with the final users subscripted to services [23]. Public telephone switches, video-on-demand servers, Internet Protocol (IP) routers, Ethernet switches, and Asynchronous Transfer Mode (ATM) switches and backup storage systems are considered as basic equipment of the CO [6]. In the CO, data and digitized voice are combined and sent downstream to customers over an optical link using a 1490 nm wavelength while the upstream uses a 1310 nm wavelength. Video services are sent downstream with a 1550 nm wavelength. In this case, there is not an upstream direction.

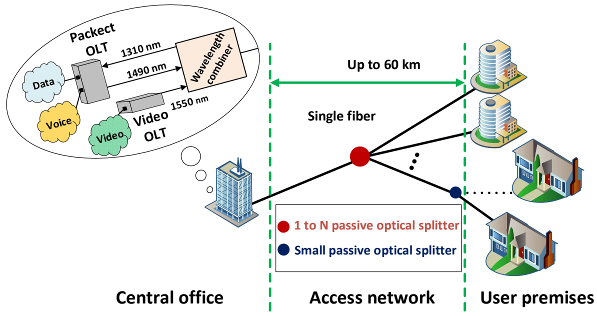


Figure 3. Architecture of a typical passive optical network.

In this PON architecture, a single-mode optical fiber strand runs from CO to a passive optical power splitter (1 to N) which divides the optical power into N separate paths to the clients. Hence, if P is the optical power entering an ideal splitter, not having excess loss, the power level going to each consumer is P/N. Splitting ratios depends on the application and number of splitting paths can vary from 2 to 64, but typically, is 8, 16, or 32. From the optical splitter, individual single-mode fibers then run to each building or to the serving equipment. In some cases, a small optical splitter is located at the end of this fiber line and then short links run from this point to the individual user premises. The maximum optical fiber transmission distance from the CO to the final user is usually of 20 km, although that value could be higher depending on the utilized ITU-Recommendation or IEEE Standard, as it shall be shown in Sections 2 and 3. For example, G-PON and XG-PON ITU-T Recommendations establish the maximum reach limit in 60 km for a split ratio of 1:64. Therefore, active devices exist only in the CO and at the user end and they must be able to support the maximum transmission range mentioned.
The transmission equipments in the PON are an Optical Line Terminal (OLT) situated at the CO and an Optical Network Terminal (ONT) at each customer's premises. When the ONT is located inside the customer's premises it is named Optical Network Unit (ONU).
The OLT is responsible for controlling the bidirectional flow of information across the optical distribution network (ODN). In the downstream direction, the OLT function is to take in voice, data and video traffic from metro network and broadcast it to all the ONT modules on the ODN. In the upstream direction, the OLT accepts and distributes multiple types of voice and data traffic from the network users.
The ONT is the interface between the ODN and customers' equipment. Hence, an opto-electrical conversion is needed within this active device. The ONT usually supports a mix of telecommunication services, including various Ethernet rates, T1 or E1 (1.544 or 2.048 Mbps) and DS3 or E3 (44.736 or 34.368 Mbps) telephone connections, ATM interfaces (155 Mbps), and digital and analog video formats [6].
In this basic PON model, the transmission medium is shared by all end users. So, a kind of transmission synchronization must be used to avoid collisions between traffic coming from different ONTs. The simplest method

is to use Time-Division Multiple Access (TDMA), wherein each user transmits information within a specific assigned time slot at a prearranged data rate. However, this does not make efficient use of the bandwidth available since many time slots will be empty when several network users do not have information to be sent back to the central office. A more efficient process is Dynamic Bandwidth Allocation (DBA) in which time slots of an idle or low-utilization user are assigned to a more active customer [24]. Nowadays, it is widely known that TDMA-PONs cannot cope with the requirements of future access networks with respect to aggregated bandwidth and allowed power budget. That power budget limits both the PON splitting ratio and the distance between the OLT and the ONT. These problems can be softened with wavelength division multiplexing (WDM)-PONs. Here, ONTs are assigned individual wavelengths, as it shall be explained in next section. Furthermore, for this type of PON, an arrayed waveguide grating (AWG), which adds lower power losses (typical insertion loss of 5 dB independent of the number of wavelengths), can be used instead of the power splitter.

1.5. Time Domain Multiplexing -Passive Optical Network (TDM-PON) vs. Wavelength Division Multiplexing -Passive Optical Network (WDM-PON)

Figure 4 shows the architecture of a time division multiplexing PON (TDM-PON) and a wavelength division multiplexing (WDM) PON [25, 26]. In both cases, the fiber plant from the OLT at a CO to the ONT at customer premise is completely passive.

A TDM-PON uses a passive power splitter as the remote node. The same signal from the OLT is broadcast to different ONTs by the power splitter. Signals for different ONTs are multiplexed in the time domain. ONTs recognize their own data through the address labels embedded in the signal.

A WDM-PON uses a passive WDM coupler as the remote node. The WDM coupler is a passive optical device with the special property of periodicity, which is the cyclic nature by which multiple spectral orders are routed to the same output port from an input port [26]. This allows for spatial reuse of the wavelength channels. Thus, signals for different ONTs are carried on different wavelengths and routed by the WDM coupler to the proper ONT. Since each ONT only receives its own wavelength, WDM-PON has better privacy and better scalability. WDM-PONs can also be combined with additional TDM techniques (see Figure 4.b). This leads to hybrid WDM-TDMA PONs and improves scalability by allowing splitting ratios of up to 1:1000 [27].

2. ITU-T RECOMMENDATION

2.1. Asynchronous Transfer Mode-Passive Optical Network (A-PON)/Broadband-Passive Optical Network (B-PON)

Following [28-35], the Full Service Access Networks (FSAN) was formed in 1995 for generating a common framework for access networks and proposed a standard to ITU-T based on (Asynchronous Transfer Mode) ATM protocol for PON in 1998. This Standard was called ATM-PON or A-PON. Afterwards, the standard was renamed to Broadband PON or B-PON. This name change was due to the inclusion of the other services, as broadcast video or Ethernet services, over the PON. The standard was updated in 2005 and some recommendations were merged. B-PON supports downlink rates of 155.52, 622.08 and 1244.16 Mb/s and uplink rates of 155.52 and 622.08 Mb/s. B-PON uses Time Division Multiplexing (TDM) and its time slots contain ATM or Physical Layer Operation, Administration and Maintenance (PLOAM) cells. The uplink uses Time Division Multiple Access (TDMA) for multiplexing the different Optical Network Units (ONU) and a DBA mechanism is implemented. The communication between OLT and ONUs is based on ATM virtual circuits, which are able to implement different levels of Quality of Service (QoS).

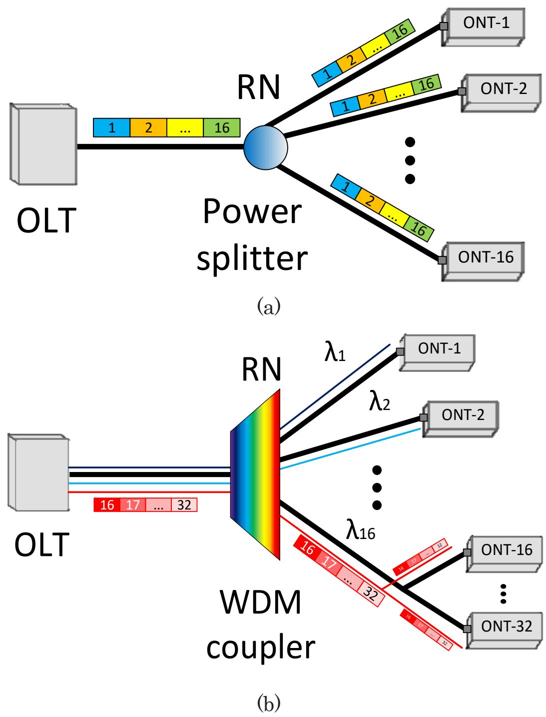


Figure 4. Architecture of TDM-PON (a) and (hybrid) WDM-(TDM) PON (b).

The maximum physical reach of B-PON is 20 km. The downlink wavelength should be at the range of 1480-1500 nm and the uplink wavelength should be at the range of 1260-1360 nm, Figure 5. The wavelength of the analog video broadcasting has been defined in the range of 1539-1565 nm.

This standard is based on the following ITU recommendation:

- G.983.1 - Broadband optical access systems based on Passive Optical Networks (PON). This recommendation was published on 1998 and reviewed on 2005.

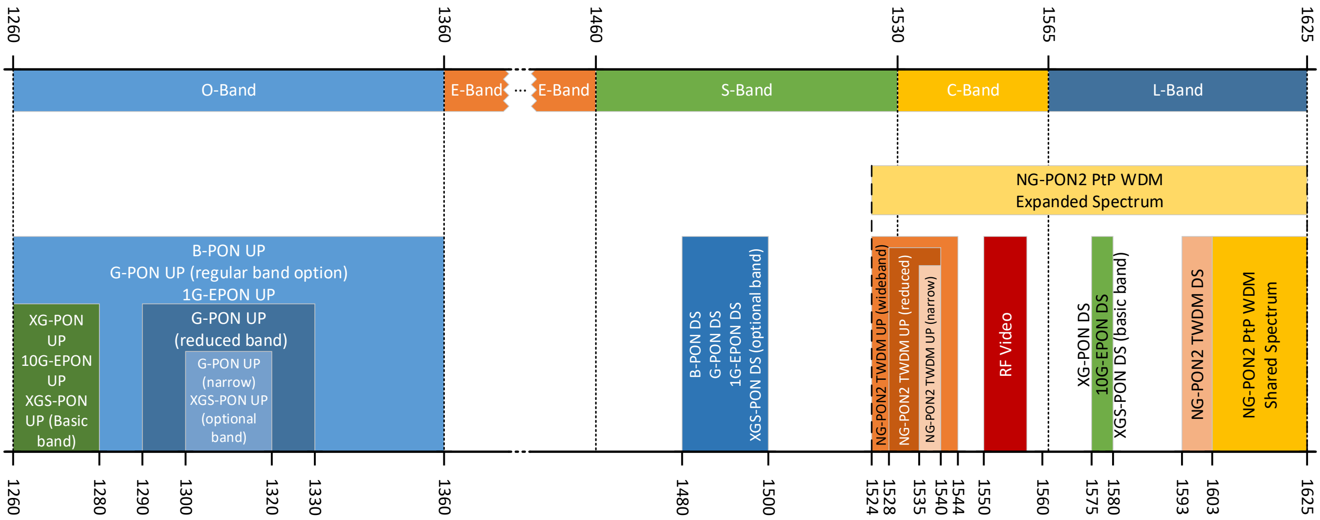


Figure 5. Wavelength range for Upstream (UP) and Downstream (DS) for B-PON, G-PON, XG-PON, NG-PON2, XGS-PON, 1G-EPON and 10G-EPON.

- G.983.2 - ONT management and control interface specification for B-PON. This recommendation was published on 2002 and reviewed on 2005 merging it with the old recommendations G.983.6 (2002), G.983.7 (2001), G.983.8 (2003), G.983.9 (2004) and G.983.10 (2004)).
- G.983.3 - A broadband optical access system with increased service capability by wavelength allocation. This recommendation was published on 2001.
- G.983.4 - A broadband optical access system with increased service capability using dynamic bandwidth assignment. This recommendation was published on 2001.
- G.983.5 - A broadband optical access system with enhanced survivability. This recommendation was published on 2002.

2.2. Gigabit-Capable Passive Optical Network (G-PON)

FSAN developed a new standard for addressing the necessities of PON with higher rates, diversity of services and a more efficient bandwidth use employing a variable length of packages [28, 34-43]. ITU-T standardized it in 2003, Figure 6. This new standard was called Gigabit-capable PON or G-PON. One of the goals of this standard is the compatibility with the previous standards. The rates supported in this standard are 1.24 and 2.8 Gb/s at the downlink and 155.52 Mb/s, 622.08 Mb/s, 1.24 Gb/s and 2.8 Gb/s at the uplinks and it can work in symmetrical or asymmetrical mode.

This standard uses the G-PON Transmission Convergence (GTC) layer framing which provides different functions as transport multiplexing between the OLT and the ONUs, PLOAM functions, DBA interface, ONU ranging and registration or FEC (Reed-Solomon (255,223)) and Downstream data encryption as optional function. ATM and G-PON Encapsulation Mode (GEM) operational modes are supported in the G-PON standard. GEM is the common mode and is similar to Generic Framing Procedure (GFP). The GEM encapsulation with segmentation capability allows TDM circuits.

TDMA is used for the uplink. The maximum physical reach supported by this standard is 20 km with a split ratio of 1:64 (considering also a maximum reach of 60km or a split ratio of 1:128 for future necessities). The downlink wavelength range is 1480-1500 nm. The uplink wavelength range are 1260-1360 nm for regular band option (using Fabry-Perot lasers), 1290-1330 nm for reduced band option (using ordinary DFB laser) and 1300-1320 nm for narrow band option (using wavelength selected lasers). The video broadcasting should be at wavelength range of 1550-1560 nm. Figure 5 shows the overview of the wavelength assignment. The required switching laser timing is 13 ns. The loss budget for G-PON is 28 dB for a B+ class budget and 32 dB for a C+ class budget.

This standard is based on the following ITU recommendation:

- G.984.1 - Gigabit-capable passive optical networks (G-PON): General characteristics. This recommendation was published on 2003 and reviewed on 2008.
- G.984.2 - Gigabit-capable Passive Optical Networks (G-PON): Physical Media Dependent (PMD) layer specification. This recommendation was published on 2003.
- G.984.3 - Gigabit-capable passive optical networks (G-PON): Transmission convergence layer specification. This recommendation was published on 2004 and reviewed on 2014 including several amendments.
- G.984.4 - Gigabit-capable passive optical networks (G-PON): ONT management and control interface specification. This recommendation was published on 2004 and reviewed on 2014.
- G.984.5 - Gigabit-capable passive optical networks (G-PON): Enhancement band. This recommendation was published on 2007 and reviewed on 2014.

- G.984.6 - Gigabit-capable passive optical networks (G-PON): Reach extension. This recommendation was published on 2008.
- G.984.7 - Gigabit-capable passive optical networks (G-PON): Long reach. This recommendation was published on 2010.

2.3. 10-Gigabit-capable Passive Optical Network (XG-PON) or Next Generation Passive Optical Network 1 (NG-PON1)

In 2010, ITU-T standardized a new standard addressing 10 Gb/s communications at the instance of FSAN called 10Gigabit-capable Passive Optical Network (XG-PON) [35, 41-51], Figure 6. This standard can be divided on two options: XG-PON1, which supports a 10 Gb/s downlink and 2.5G b/s uplink and a future development XG-PON2, which supports a symmetrical 10 Gb/s PON. This last option (XG-PON2) has finally become in an independent standard (XGS-PON).

XG-PON has to coexist with the previous standard, G-PON. XG-PON use a G-PON like frames and protocols for allowing the coexistence between both standards and also it shall support Ethernet frames. This framing sublayer is called XG-PON transmission convergence (XGTC) and the encapsulation method is called XGEM. XGEM allows individual traffic flows, fragmentation and data privacy. This standard requires a strong mutual authentication to protect the PON and power savings options on the equipment. The used FEC in this standard is a RS (255,223). XG-PON upstream is burst oriented and employed TDMA to allow the access to the common medium.

The maximum physical reach of this standard is between 20 km and 60 km, with a split ratio has to be 1:64 or 1:128. The maximum requirements have not to be fulfilled at the same scenario.

The uplink wavelength range is 1260-1280 nm and the downlink wavelength range is 1575-1580 nm, as shown in Figure 5. The loss budget for XG-PON are 29 dB for a N1 class budget, 31 dB for a N2 class budget, 33 dB for an E1 class budget and 35 dB for an E2 class budget for a PIN and APD receiver cases.

This standard is based on the following ITU recommendation:

- G.987 - 10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms. This recommendation was published 2010 and reviewed on 2012.
- G.987.1 - 10-Gigabit-capable passive optical networks (XG-PON): General requirements. This recommendation was published on 2010 and reviewed on 2016.
- G.987.2 - 10-Gigabit-capable passive optical networks (XG-PON): Physical Media Dependent (PMD) layer specification. This recommendation was published on 2010 and reviewed on 2016.
- G.987.3 - 10-Gigabit-capable passive optical networks (XG-PON): Transmission Convergence (TC) layer specification. This recommendation was published on 2010 and reviewed on 2014.
- G.987.4 - 10-Gigabit-capable passive optical networks (XG-PON): Reach extension. This recommendation was published on 2012.
- G.988 - ONU Management and Control Interface (OMCI) specification. This recommendation was published on 2010 and reviewed on 2012.

2.4 Next Generation Passive Optical Network 2 (NG-PON2)

In 2015, Figure 6, ITU standardized a new standard proposed by FSAN [35, 41, 52-58]. This standard is called 40Gigabit-capable Passive Optical Network (NG-PON2). NG-PON2 is able to aggregate downlink for residential and business application, mobile backhauling, and other services.

This standard has been designed to be compatible and coexist with all the previous standards. And as some companies have described: NG-PON2 can be seen as an orderly augmented version of XG-PON1, with a large amount of component reuse [59]. The Transmission Convergence (TC) layer is the protocol layer of NG-PON2, including the dynamic bandwidth allocation (DBA) also presents in the previous ITU standards.

This standard proposes two types of links: The links based on Time and Wavelength Division Multiplexing (TWDM) and the links based on Point-To-Point Wavelength Division Multiplexing (P2P WDM). TWDM links consist in 4 or 8 TWDM channels with rates of 2.5 or 10 Gb/s for the uplink and the downlink. The NG-PON2 has to support a minimum of the aggregated traffic of 40 Gb/s at the downstream and 10Gb/s at the upstream. P2P WDM channels can support rates of 1.25, 2.5 or 10 Gb/s depending on the P2P WDM client.

The physical reach distance of this standard should be at least 40 km, with the possibility of reach 60 km, and a differential fiber distance of 40 km. Also, it has to be able to work with a split ratio of 1:256. The P2P WDM PON can supports two types of Optical Distribution Networks (ODN): Wavelength-Selected ODN (WS-ODN) and Wavelength Routed ODN (WR-ODN). WS-ODN uses tunable filters allowing to select the channel at the ONU and the WR-ODN uses wavelength splitters at ODN to routing the channels. Compatible systems with WS-ODN are mandatory for legacy ODN. In addition, colorless ONUs are required for an operation cost reduction. The loss budget for NG-PON2 has to be compatible with the XG-PON one (29 dB for a N1 class budget, 31 dB for a N2 class budget, 33 dB for an E1 class budget and 35 dB for an E2 class budget). NG-PON2 has two types of upstream links: without preamplifier (Type A) and with preamplifier (Type B) at the OLT. Type A links need more powerful ONUs and Type B links need more sensitive OLT. In addition, NG-PON2 defines 3 types of wavelength tuning time classes: Class 1 requires less than 10 µs of tuning time, Class 2 requires between 10 µs and 25 µs of tuning time and Class 3 requires between 25 µs and 1 s of tuning time. Class 3 devices are usually based on thermal effects. Class 2 devices will allow sub-50 µs protection and Class 1 will enable future dynamic bandwidth and wavelength allocation. NG-PON2 introduces requirements on crosstalk because it uses wavelength multiplexing. The Out-Of-Channel (OOC) interference penalty has to be less

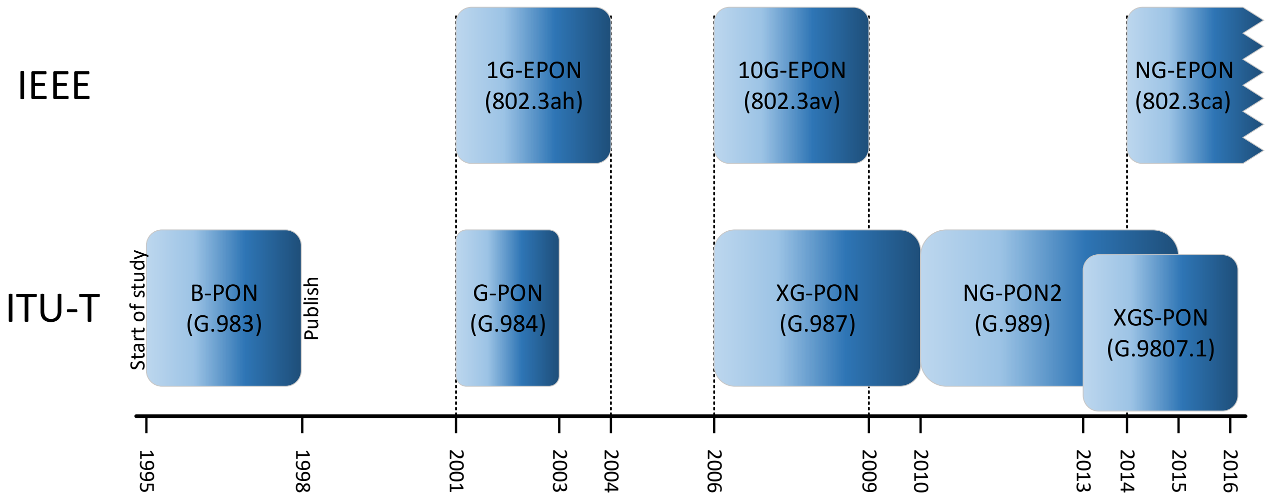


Figure 6. Evolution of the Standard with the year of the start to discuss about the standard and the year of its publication.

than 1 dB for the upstream and less than 0.1 dB for the downstream. The Out-of-Band (OOB) interference penalty has to be less than 0.1 dB for both directions.

In NG-PON2, the wavelength stability requirements have been defined using the Maximum Spectral Excursion (MSE) in order to prevent a power leaking between channels and to ensure that the links operate property inside their own channels. The channel spacing of the TWDM downstream is 100 GHz and has to have a MSE of ±20GHz. The channel spacing of the TWDM upstream can be in the range of 50 to 200 GHz and for example a channel spacing of 50GHz has a MSE of ±12.5GHz, a channel spacing of 100 GHz has MSE of ±20GHz and a channel spacing of 200 GHz has MSE of ±25GHz. The laser switching on/off can cause a short-term spectral excursion, which also have to be inside the MSE requirements. The wavelength calibration accuracy of the TX tunable laser of the ONUs defines three categories: sufficient calibration, loose calibration and no calibration. If the laser is not calibrated, they can be out of the MSE limit and wavelength-locking systems have to be implemented.

The wavelength range for TWDM downstream is 1596-1603 nm and for the TWDM upstream is 1524-1544 nm for wideband option, 1528-1540 nm for reduced option and 1535-1540 nm for the narrow option, as shown in Figure 5. In the case of P2P WDM up/downstream, the wavelength range is 1524-1625 nm for the expanded spectrum option and the 1603-1625 nm for the shared spectrum option.

This standard supports multiple wavelengths and has enough flexibility for the adaptation to the future necessities on the 100G and beyond age.

This standard is based on the following ITU recommendation:

- G.989 - 40-Gigabit-capable passive optical networks (NG-PON2): Definitions, abbreviations and acronyms. This recommendation was published on 2015.
- G.989.1 - 40-Gigabit-capable passive optical networks (NG-PON2): General requirements. This recommendation was published on 2013 and reviewed on 2016.
- G.989.2 - 40-Gigabit-capable passive optical networks 2 (NG-PON2): Physical Media Dependent (PMD) layer specification. This recommendation was published on 2014.
- G.989.3 - 40-Gigabit-capable passive optical networks (NG-PON2): Transmission convergence layer specification. This recommendation was published on 2015.

2.5. 10-Gigabit-Capable Symmetric Passive Optical Network (XGS-PON)

FSAN has been working since 2013 in the new standard XGS-PON, which was cited originally as XG-PON2 in the XG-PON standard [41, 60]. This new standard, 10-Gigabit-Capable Symmetric Passive Optical Network (XGS-PON), has been released on 2016, Figure 6. This standard has been designed for providing access services for residential and business, and for mobile backhauling.

XGS-PON Transmission Convergence (TC) framing sublayer is used in this standard, which allows implementing DBA. This standard uses XGEM framing. The OLT has to support dual line-rates (2.5 Gb/s and 10 Gb/s) to ensure the coexistence with previous standards (XG-PON). The downlink implements TDM for multiplexing the different ONUs and the upstream implements TDMA for allowing the access to the different ONUs to the common medium. Also, the FEC is implemented, specifically Reed-Solomon (255,223).

The minimum split ratios for XGS-PON should be 1:64 for ensuring the coexistence with G-PON, but the operators have shown interest on split ratios of 1:128 and 1:256. In addition, XGS-PON has to support at least 20 km of maximum fiber distance and the TC layer has to support 60 km of fiber distance with a maximum fiber distance of 40 km, to allow the coexistence with XG-PON.

This standard has two wavelength ranges available: basic and optional wavelength. The basic wavelength range is the same than in XG-PON (downstream=1575-1580 nm, upstream=1260-1280 nm), Figure 5. In order to support XGS-PON and legacy XG-PON ONUs in the basic wavelength, dual-upstream rate TDMA and TDM at the downstream is used. If the basic range is used, the legacy G-PON ONUs co-existence is direct. The optional wavelength range is the same than in narrow upstream range of G-PON (downstream=1480-1500 nm, upstream= 1300-1320 nm). In the optional range, legacy G-PON ONUs is not supported and legacy XG-PON are supported with wavelength multiplexing. This two wavelength range can be used at the same time.

The loss budget of XGS-PON depends on the wavelength range selected. If the basic wavelength range is used, the loss budget is equal to the XG-PON one (29 dB for a N1 class budget, 31 dB for a N2 class budget, 33 dB for an E1 class budget and 35 dB for an E2 class budget). In the case of using the optional wavelength range, the loss budget is the G-PON loss budget (28 dB for a B+ class budget and 32 dB for a C+ class budget).

This standard is based on the following ITU recommendation:

- G.9807.1 - 10-Gigabit-capable symmetric passive optical network (XGS-PON). This recommendation was published on 2016.

3. IEEE STANDARDS

3.1. 1 Gigabit Ethernet Passive Optical Network (1G-EPON)

In 2001, IEEE formed the 802.3ah task force group, also called Ethernet in the First Mile [28, 34, 35, 41, 61]. In 2004, this group defined the 1G-EPON with the standard IEEE Std 802.3ah-2004, Media Access Control Parameters, Physical Layers, and Management Parameters for Subscriber Access Networks.

The 1G-EPON consists in PON with symmetrical 1 Gb/s transmission rate. The minimum split ratio for 1G-EPON is 1:16 and the reach distances can be 10 km (1000BASE-PX10-D PMD and 1000BASE-PX10-U PMD) or 20 km (1000BASE-PX20-D PMD and 1000BASE-PX20-U PMD). The wavelength allocation ranges are 1480-1500 nm for downlink and 1260-1360 nm for uplink band option, Figure 5. The loss budget for 1G-PON is 29 dB for a PX30 class budget and 33 dB for a PX40 class budget. The required laser on/off timing is 512 ns.

The 1G-EPON protocol is a Multipoint Control Protocol (MPCP), which coordinates the communication between the OLT and ONUs in a shared PON medium, and it is similar to the Point to Point (P2P) Ethernet. 1G-EPON upstream works in a burst mode, i.e. TDMA. 1G-EPON downstream has a continuous signal stream and clock synchronization and the ONU use a loop timing for the upstream burst mode transmission obtaining the clock from the downstream received signal. The 1G-EPON uses 8B/10B code line (8 data bits encoded as 10 line bits) which produces a DC balanced output and easy clock recovery but it needs to increase the symbol rate to 1.25 Gb/s in order to deliver a 1 Gb/s of data. The FEC is an optional option and it uses a RS (255,239). If the vendors are interested, 1G-EPON can implement DBA, OAM sublayer, encryption and protection mechanisms, but it is not specified at the standard. In order to implement fixed bandwidth TDM circuits is necessary to use circuit emulation.

3.2. 10 Gigabit Ethernet Passive Optical Network (10G-EPON)

In 2006, the 10G-EPON study group was established and they standardized a new standard IEEE Std 802.3av-2009 Physical Layer Specifications and Management Parameters for 10 Gb/s Passive Optical Networks (10G-EPON) in 2009 [35, 41, 50, 62-65].

The 10G-EPON standard considers a symmetrical 10G/10G transmission rate PON and asymmetrical 10G/1G transmission rate PON (10 Gb/s downstream and 1 Gb/s upstream). The loss budget for 10G-PON are 29 dB for a PR30 and PRX30 class budget and 33 dB for a PR40 and PRX40 class budget. The split ratios considered at this standard are 1:16 and 1:32 and minimum reach distances of 10 km or 20 km. The required laser switching timing is 512 ns. The wavelength ranges in order to maintain the co-existence with 1G-EPON are 1260-1280 nm for the uplink and 1575-1580 nm for the downlink.

The co-existence between 10G-EPON and 1G-EPON in the downstream is solve using WDM multiplexing because their wavelength bands are not overlapped. In the case of the upstream, both standards bands are overlapped and a dual-rate burst receiver and dual rate DBA has to be used, moving all the co-existence issues to the electrical domain.

The 10G-EPON protocol is a modified MPCP, which orchestrate the communication between OLT and ONU. The 10G-EPON use 64B/66B code line, which produces less overhead than the 8B/10B code line of 1G-EPON, and so the symbol rate has to be 10.3125 Gb/s for delivering a 10 Gb/s of data. In 10G-EPON, the FEC is mandatory and it uses a RS (255,223).

3.3. Next Generation Ethernet Passive Optical Network (NG-EPON)

In 2014, the NG-EPON study group starts to consider the next standard for the EPON networks: IEEE Std 802.3ca Next Generation Ethernet Passive Optical Network (NG-EPON). This study group continues with its analysis and the standard has not been released at this moment [41, 66, 67]. This standard considers a multi-wavelength EPON with an aggregate capacity of at least 40 Gb/s (40G-EPON) in both directions and the possibility of extending the aggregated capacity to 100 Gb/s (100G-EPON). Also, a single-wavelength EPON is considered with symmetric rates of at least 25 Gb/s (25G-EPON) or a downstream rate of 25 Gb/s and an upstream rate of 10 Gb/s (25/10G-EPON).

The split ratios supported by NG-EPON has to be similar to the previous EPON standards (1G-EPON and 10G-EPON) and the reach distance has to be at least 20 km with a differential reach of at least 10 km. If the loss budget is low class (≤20 dB), the split ratio has to be 1:16 and the reach distance has to be at least 10 km. If the loss budget is medium class (≤24 dB), the split ratio has to be 1:32 and the reach distance has to be at least 10 km. If the loss budget is high class (≤29 dB), the split ratio has to be

1:32 and the reach distance has to be at least 20 km. If the loss budget is extended class (≤33 dB), the split ratio has to be 1:64 and the reach distance has to be at least 20 km.
The coexistence with the previous standards will require triple-rate burst receiver at the OLT in the case that there is still legacy 1G-EPON and 10G-EPON ONUs in the ODN.
This standard considers to use NRZ has a modulation but also multi-level modulation schemes as duobinary, PAM-4 or OFDM. Also, using WS-ODN and WR-ODN as ODN is under consideration in NG-EPON. The wavelength plan for NG-EPON is under discussion and there are 4 possible plans for the wavelength allocation:

- Plan A: the downstream is placed at 1550-1560 nm and the upstream is placed at 1530-1540 nm.
- Plan B: the downstream is placed at 1480-1500 nm and the upstream is placed at 1530-1540 nm.
- Plan C: the downstream is placed at 1595-1605 nm and the upstream is placed at 1530-1540 nm.
- Plan D: the downstream is placed at 1550-1560 nm and the upstream is placed at 1340-1360 nm.

4. FUTURE PASSIVE OPTICAL NETWORK (PON)

In this section we provide an overview over future trends in the field of passive optical networks (PONs). In particular, some research projects and their main milestones have been analyzed. Furthermore, a brief study of advances technologies for future PONs is also given.

4.1 Research Projects

DIStributed Core for unlimited bandwidth supply for all Users and Services (DISCUS)

DISCUS project was started in 2012 and it was concluded in 2015. DISCUS project consists of an end-to-end solution for ubiquitous broadband services in order to cost and energy saving [68]. DISCUS project is based on the idea of sharing the network capacity among large number of users through a long-reach PON (LR-PON) and flap optical core network, as it can be seen in Figure 7.
DISCUS nodes are the interface between core networks and LR-PON. DISCUS nodes connect with a long reach fiber, over 125 km, and large split distribution networks, up to 512 physically and up to 1024 logically [69], at the LR-PON and with wavelength-switched optical network at the flat optical core network.
Dynamically reconfigurable 10G Time-Division Multiplexing (TDM) Dense Wavelength Division Multiplexing (DWDM) LR-PONs coexists with business 100G dedicated channels and wireless fronthaul [70]. Amplifier nodes are integrated on the LR-PON in order to support these heterogeneous services with some functionalities as some processing for low latency services for wireless front-hauling [70].
Finally, the Optical Distribution Network (ODN) can be efficiently adapted to dense populated areas with larger splitting ratios or to sparsely populated rural areas wilt longer distribution networks. The DISCUS architecture allows the coexistence and management of these heterogeneous services [69].

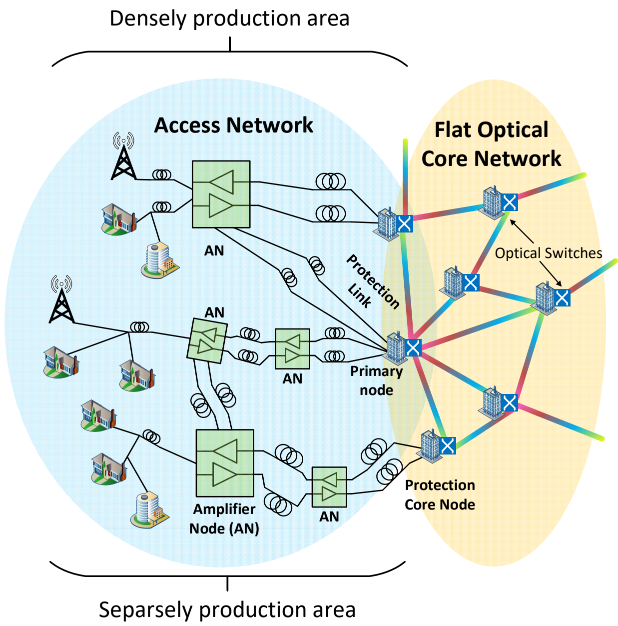


Figure 7. Proposed LR-PON network concept by DISCUS project.

Scalable Advanced Ring-based passive Dense Access Network Architecture (SARDANA)

SARDANA project was started in 2008 and it was concluded in 2011. SARDANA project consists of a Long-Reach Passive Optical Network (LR-PON) based on WDM double-fiber ring with Remotes Nodes (RN) that connect with secondary single-fiber wavelength dedicates trees [71-73], as shown Figure 8.

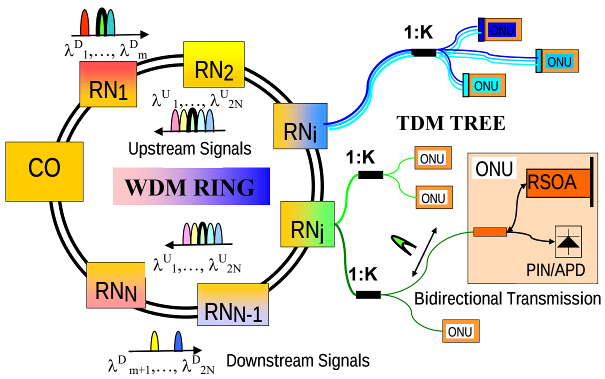


Figure 8. SARDANA network architecture.

SARDANA project includes remote amplification employing Erbium Doped Fibers (EDFs) pumped form the Central Office (CO) in order to compensate the RN insertion losses [71]. This remote pumps laser also provides with an extra Raman amplification on the ring [74].
SARDANA LR-PON is based on a WDM ring of 100 km with 32 wavelengths with 16 RN that can serve to up to 1024 users [74] employing TDM of the single-wavelength trees. This SARDANA flexible WDM/RDM architecture

allows high data rates (10 Gbps) with power budgets of 30 dB over remotely amplified LR-PON [73].

Photonic Integrated Extended Metro and Access Network (PIEMAN)

PIEMAN project was started in 2006 and it was concluded in 2009. PIEMAN project consists of all-optical integrated metro and access network [75, 76].
PIEMAN project allows 10 Gbps downstream and 10 Gbps upstream integrating and simplifying the metro and the access network [75]. PIEMAN project combine a high splitting PON with multiwavelength transmissions. The employed Dense WDM (DWDM) consists of 32 wavelengths spaced 50 GHz where the 10 Gbps of each wavelength is split among 512 users employing TDM [75, 76]. The ODN reaches distances of 100 km employing optical amplifiers at the remotes nodes [75]. Figure 9 shows PIEMAN system architecture.
PIEMAN project implemented colorless ONUs transceivers based on reflective electro-absorption modulators with semiconductor optical amplifiers or based on low-cost tunable lasers as transmitters [76] and 10 Gbps avalanche photodiode (APD) as receivers.

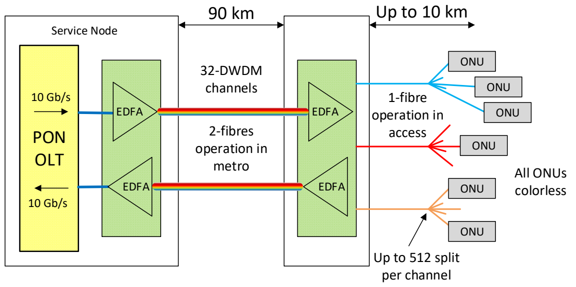


Figure 9. PIEMAN system architecture.

COst-effective COherent Ultra-dense-WDM-PON for lambda-To-the-user access networks (COCONUT)

COCONUT project was started in 2012 and it was concluded in 2016. COCONUT project consists of an ultra-Dense Wavelength Division Multiplexing (uDWDM) access networks based on cost-effective and reduced power consumption coherent technologies [77].
The COCONUT project looks for an increased loss budget for extended distribution networks, node consolidation and a higher number of ONUs [77]. In addition, COCONUT project requires a co-existence with legacy optical solutions.
COCONUT project allows wavelength spacing of 6.25 GHz with 1.25 Gbps data rate. Coherent ONUs of COCONUT project allows the operation without optical filter, provided of a high receiver sensitivity and a reduced crosstalk [77].
COCONUT project has explored different solution for coherent ONUs. COCONUT receiver is based on simple 3x3 fiber couple with polarization independent operation [78] or simplified polarization heterodyne receivers [79]. COCONUT transmitters are based on Distributed Feed-Back (DFB) lasers which can operate as ASK mode [78] or DPSK mode [79]. COCONUT transceivers allow 10 Gbps transmissions with power budgets of 40 dB.

Gigabit Access Passive Optical Network Using Wavelength Division Multiplexing (GigaWaM)

GigaWaM project was proposed in 2008 [80] and it was concluded in 2012 [81]. Figure 10 shows the GigaWaM system overview [81]. It can potentially deliver per-user datarates of 2.5 Gb/s upstream and 10 Gb/s downstream to 64 end-users over 26 km SSMF. To make that possible, all essential optical subsystems of a WDM-PON access network (see Figure 4.b) have been developed. That is the Central Office (CO), the Remote Node (RN) and the Optical Network Unit (ONU). In the GigaWaM transmission system, upstream channels are transmitted in the C-band (1533.073–1558.173 nm), whereas downstream channels are established within the L-band (1573.810–1599.561 nm).

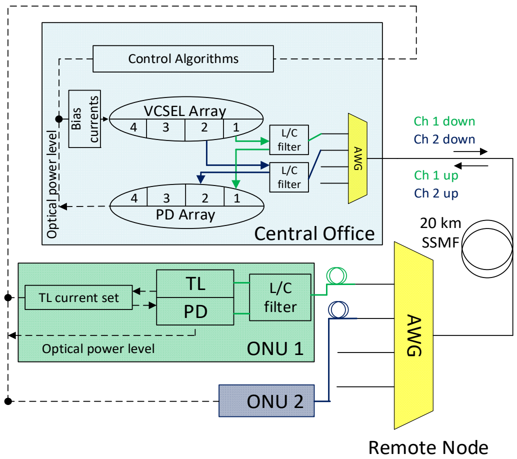


Figure 10. GigaWaM system overview [81].

Central Office (CO). The CO is largely integrated in a single Planar Lightwave Circuit (PLC) in which both a Vertical Cavity Surface-Emitting Laser (VCSEL) array and a photodiode (PD) array can be attached using novel hybridization techniques. The VCSEL array can work in whole L-band. In this way, to make a fine tune of a wavelength and keep it locked to the corresponding channel, a continuous bias current is required. L-band/C-band (L/C) filters are used to separate up and downstreams in the CO and an integrated AWG is used to combine different wavelengths to the same fiber.
Remote Node (RN). The GigaWaM RN, which is a passive element, consists of a Fiber Array Unit (FAU), a PLC-based AWG, and a Temperature Compensation Unit (TCU) block whose main aim is to reduce the RN temperature dependency.
Optical Network Unit (ONU). The ONU includes a PD, L/C filters, a modulated grating Y-branch laser with monolithically integrated semiconductor optical amplifier (MGYSOA) and a microcontroller that reads the temperature and sets the wavelength. The Tunable Laser (TL) can work in 10 Gb/s operation mode across the full C-band.
In the GigaWaM system, the link establishment and maintenance between CO and ONUs is centrally

controlled by computer algorithms via supervisory channels (dashed lines in Figure 10). Therefore, the received power of the upstream channels at the CO must be monitored as well as the temperature of each ONU. Using that information, a fine tune of the TL and VCSEL wavelengths can be accomplished.

Optical Access Seamless Evolution (OASE)

OASE project started on January 2010 and ended on February 2013 focused on providing guidelines for migration strategies from initial PON deployments towards Next Generation Optical Access (NGOA) solutions. As operators of first FTTH and PON networks were facing an exponential increase of traffic demand and several "next generation" technologies and architectures have been investigated, the OASE project aimed providing recommendations for OA networks upgrade to diverse economical actors as: Physical Infrastructure Providers (PIP), Network Providers (NP), and Service Providers (SP). The PIP is the owner or economical responsible for ducts, fibers, passive equipment as splitters, racks, etc. The PIP provides a leasing service of the dark fiber infrastructure to NPs, who own or manage the active equipment required for transmission and provide end-to-end connectivity. Finally, SPs provide different services on top of this [82]. Each of those economical actors deal with different challenges. For example, PIPs face high up-front investments, low economies of scale and regulations, while NPs are characterized by high recruiting costs and higher economies of scale. And SPs are typically dominated by marketing, customer relations and service innovation.

One of the main objectives was to minimize the Total Cost of Ownership (TCO), to analyze the capability of each NGOA solution to increase energy efficiency, as well as to provide and evolution towards an "open access network" scenario, so that several NPs and SPs can share a common infrastructure.

As initial optical access solutions, for further migration and benchmarking, G-PON and Active Optical Networks (AONs), Ethernet point-to-point, also referred as AON P2P, were considered. A detailed analysis of alternative NGOA solutions was done in OASE covering System-Level, Architecture-Level and Techno-economical evaluations. Finally, cases for business feasibility were provided for 3 main identified economical factor: PIP, NP and SP.

A very good and detailed summary of the main results of this project can be found in [82]. Though many NGOA solutions were considered in OASE project, they can be classified in 4 main groups of solutions as: WDM-PON, Hybrid WDM/TDM-PON, WDM-PON backhaul and NG-AON.

Under the classification of WDM-PON, several subcategories as considered as: Wavelength-selected (WS-) WDM-PON having a power-split Optical Distribution Network (ODN); or Wavelength-routed (WR-) WDM-PON with a WDM-filtered ODN; and Ultradense (UD-) WDM-PON, as a variant of WS-WDM-PON requiring coherent receivers and implementing an ultradense channel spacing, therefore compatible with power-split or power-split plus WDM-filtered ODN (hybrid ODN) as shown in Figure 11.

Hybrid WDM/TDM-PON can be implemented on the same hybrid ODN, as shown in Fig 11 and refers to the Time and Wavelength Division Multiplexing (TWDM) described in Section 2.4. Among the diverse variations, also semi-passive hybrid WDM/TDM-PON were considered, where semi-passive refers to ODN in which the AWG of RN1 in Figure 11 is replaced by an active reconfigurable optical switch, as e.g. a Wavelength Selective Switch (WSS), able to switch wavelengths or set of wavelengths to different distribution fibers and assign resources in a flexible and reconfigurable way.

Finally, WDM-PON Backhaul refers to a hybrid AON/PON architecture where two typical PON-based stages (corresponding to the backhaul and the first mile respectively) are connected by an active element terminating and regenerating the optical signal. And NG-AON is based on active Remote Nodes (RN) places somewhere in the ODN, typically as evolution of initial standard star topology (also referred as active star or AS-AON).

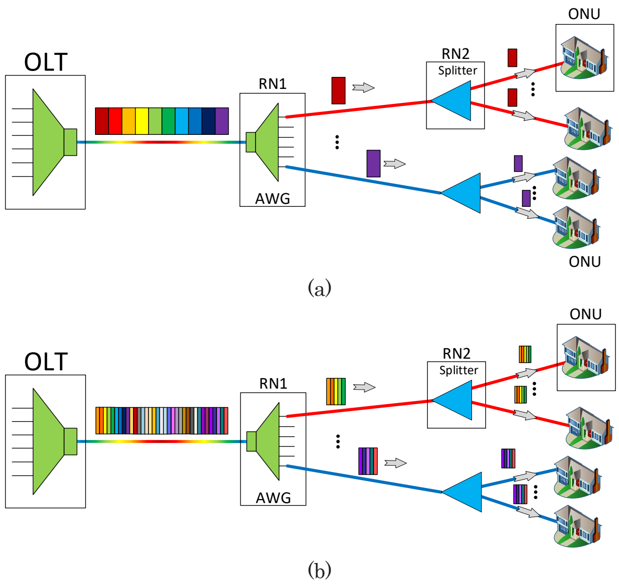


Figure 11. Considered WDM-based NGOA: (a) Hybrid PON (HPON) and (b) UDWDM.

The analyses performed in OASE show that there is not a major difference among those NGOA regarding power consumption, neither regarding System level analysis (capability for all of the NGOA to perform properly and provide, e.g. $\geq$1 Gbps peak bit rate and 300 or 500 Mbps guaranteed bit rate per client). After several recommendations for business cases to PIPs and NPs a general recommendation arises in the form of Open Access (sharing) infrastructures, as the basis for considerably reducing investment costs and enabling competition between service providers, those leading to lower prices and more opportunities for end users. On the other hand, a detailed techno-economic analysis, extended in [83, 84], shows network consolidation (reduction of sited and active nodes) as a principal way, when possible, for reducing the

TCO. Finally, OASE project recommends the TWDM solution, later on standardized in NG-PON2 to provide high guaranteed data rate with the lowest infrastructure cost for greenfield deployments with G-PON and different solutions for brownfields, depending on the previous infrastructure and node-consolidation scenarios.

A converged copper-optical-radio OFDMA-based access network with high capacity and flexibility (ACCORDANCE)

ACCORDANCE project was started in 2010 and it was concluded in 2013. ACCORDANCE project introduces OFDM/OFDMA in Passive Optical Networks (PON) at physical and Medium Access Control (MAC) level [85].
ACCORDANCE project proposes as topology a single Optical Line Termination (OLT) with several Optical Network Units (ONUs), as it can be seen in Figure 4. The Remote Node (RN) consists of a power splitter or a wavelength multiplexer and can include amplification for an extended reach network [85]. ACCORDANCE project allows targeted service clustering [85] allowing a flexible Dynamic Bandwidth Assignment (DBA), so the exact spectrum depends on OFDM transmission scheme.
ACCORDANCE project also proposes intensity and coherent modulation transceivers. The ACCORDANCE intensity modulated transceivers are based on OFDM with Hermitian symmetry to obtain real symbols. The ACCORDANCE coherent modulated transceivers can be based on field modulation with RF upconversion over a MZM or modulation with an optical IQ modulator. ACCORDANCE project allows adaptive modulation changing the order of the QAM modulation of the OFDM subcarriers, so different data rates can be delivered.

Innovative coherent detection Optical Access Networks (INVENTION)

INVENTION project was started in 2016 and it is still until development. Hitherto, it has been demonstrated a 56 Gb/s multi-band Carrierless Amplitude and Phase modulation (CAP) signal transmission over an 80 km on a SSMF [86] enabling long reach transmission such as inter-data center connections. In that work, it has been proposed the use of differential QAM encoding/decoding together with a Multi-Modulus Algorithm (MMA)-based equalization to deal with the sensitivity of CAP signals to timing jitter or inaccurate clock recovery. Figure 12 shows the overview of the INVENTION transmission system. The transmitter consists of an offline multi-band CAP signal generator, an 80-GS/s Digital-to-Analog Convertor (DAC), a Tunable Laser (TL), and a differentially driven Mach–Zehnder intensity Modulator (MZM). Following the MZM, a multiplexer (MUX) with a 50-G DWDM grid is used and its output is amplified by a booster Erbium-Doped Fiber Amplifier (EDFA). Then the signal is transmitted to the receiver using 80 km SSMF.
The received signal is amplified using an EDFA at the receiver (RX). The optical signal is injected into a PIN-TIA trough a 50 GHz de-multiplexer (De-MUX). The detected multi-band CAP signal is then converted into a digital signal by an ADC sampling at 80 GS/s. The digital signal is then sent to a computer and undergoes offline signal processing. The INVENTION transmission system is characterized by presenting of 0.5 dB chromatic dispersion (CD) penalty and 28 dB OSNR at a BER of $3.8 \cdot 10^{-3}$.

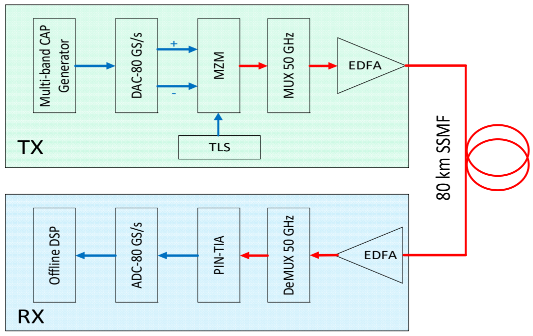


Figure 12. Overview transmission system for 56-Gb/s multi-band CAP [86].

Coherent Broadband Networks Embedding Smart Photonics for Cost-Effective Quintuple-Play (WARP-5)

WARP-5 project was started in 2013 and it was concluded in 2016. In the field of Access PONs, this project has proposed a novel fully-passive coherent PON implementation that can increase the split ratio from 1:1000 per-PON to 1:3072 with a bit rate of 1 Gb/s per-user [87]. To reach that, a remote Erbium-Doped Fiber Amplifier (EDFA) is employed. The required energy to perform the amplification is obtained from the background noise which can be spectrally reshaped in the terminal of the EDFA. The total loss budget for 40 km as a maximum reach distance is of 52 dB. WARP-5 also proposes a low-cost transmitter that can generate QAM formats with up to 16 levels [88]. In this way, the transmitter can be adapted to work with different symbol rate more efficiently. The transmitter is based on an Electroabsorption Modulator (EAM)/ Semiconductor Optical Amplifier (SOA) that can generate digital formats with spectral efficiency of up to 4 bits/symbol, delivering up to 4 Gb/s per-user bandwidth with PON loss budgets up to 49 dB.
In the field of coherent Metro-Access PONs, WARP-5 advances the design of a passive resilience switch [89] that enables dual-homing PON as it is shown in Figure 13. The optical switching is between the feeder and drop segments of a PON and it is based on Micro-Opto-Electromechanical System (MOEMS) technology that can work in latching operation guaranteed that there is no steady-state power consumption once the network is configured. The required switching energy for the proposed node solution is of -10 dBm and its switching speed is 10 ms.

4.2. Advanced Technologies

As describe in Sections 2 and 3, main standardization bodies, ITU-T and IEEE have been progressively proposing recommendations for PONs providing from

155.52 Mb/s initially, towards 40Gb/s, and 100Gb/s is nowadays under discussion.
This quick progress in provided data rate, as well as enhanced physical reach distance and higher number of users, is fueled by background research in advanced technologies, providing new features and performances. On the one hand, stacking pairs of wavelength operating at the XG-PON rates, implementing the TWDM technique introduced previously, 40Gb/s was provided for downstream and 10Gb/s for upstream, supporting 20km distance and 1:512 split ratio, while providing coexistence with commercially deployed G-PON and XG-PON systems [90].
On the other hand, as the requirements for higher data rate and longer reach rise, advanced modulation formats beyond Non-Return-to-Zero (NRZ) and On-Off-Keying (OOK) are required. One of the main challenges for serial bitrates higher than 10 Gb/s are the decreasing Chromatic Dispersion (CD) tolerance, leading to either reduced fiber reach and/or reduced optical power budget [91]. Not to mention that higher bandwidth components would be needed leading to higher cost electronics, devices and overall system.

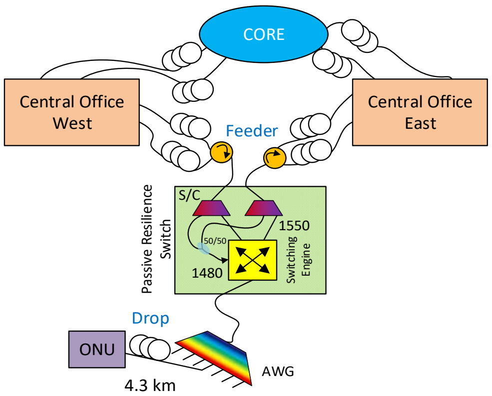


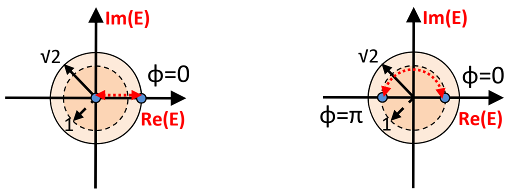
Figure 13. Dual-homing PON with fully passive resiliency node [89].

Several technologies have been investigated and identified to have the potential to impact future PONs standards and many of them are related with advanced modulation formats and their implementation as: digital signal processing (DSP), subcarrier techniques such as Discrete Multi-tone (DMT), Orthogonal Frequency-Division multiplexing (OFDM) and coherent detection [91].

Advanced Modulation Formats

Advanced modulations formats for optical communications has been deeply studied. The readers interested in a good description of advance optical modulation formats can find followed [92]. Also a more specific work on modulation formats for 100G and beyond [93] was addressed before the advent of high speed DSP technologies. Although those modulation formats were originally developed for very long reach, core networks, some of them are also under deployment in access networks as it will be seen.

Following the recent standards also supporting P2P WDM channels, and colorless ONUs, advanced modulation formats based in phase modulation of the optical signals as Differential Phase Shift Keying (DPSK) at 40 Gb/s has been tested in PON [94]. Figure 14 shows the symbol diagrams of representing the complex electromagnetic field of optical signals of OOK and DPSK. One of the advantages of using DPSK instead of OOK is that the symbol spacing, Figure 14b, is increased by √2 compared to OOK for a fixed average optical power [95]. This increased symbol distance helps DPSK to accept a √2 larger standard deviation of optical field noise for equal BER than OOK, aiding high capacity long reach transatlantic communications [96]. Another advantage of DPSK modulation format, is that, by proper phase modulator implementations, the optical signal maintains a constant intensity value, as shown in Figure 14. In the contest of PON, this permits to reuse the downstream DPSK signal carrier as upstream by using the Reduced Modulation Index (RMI) [94] by a colorless ONU. It was checked that due to accumulated CD, the upstream remodulated OOK-RMI signal is greatly affected. This has been leading to relative reduced transmission distances, motivating further studies.



(a) (b)

Figure 14. Symbol diagrams representing the complex electromagnetic field of optical signals, (a) OOK, (b) DPSK.

The required CD tolerances and high sensitivity for Long-Reach Passive Optical Networks (LR-PON) arrived by hand of OFDM, DMT modulation formats in general and coherent detection assisted by DSP.
Although OFDM theory has considerable extent, a relative intuitive idea can be gained by comparing Single Carrier (SC) as OOK or DPSK modulation formats with DMT and OFDM in Figure 15. In order to achieve the same overall transmitted data rate, either a SC modulated by a serial high data rate can be transmitted over certain frequency spectrum, or a set of narrower tributaries can be modulated in parallel as shown in Figure 15. In fact, DMT would lead to traditional WDM if subcarrier frequencies are replaced by wavelengths. Comparing both approaches, the very high serial symbol rate of the SC requires very short symbol times (T), that will be more affected by non-ideal channel propagation. For example CD, usually expressed in units of picoseconds per nanometer and kilometer (ps/(nm·km)), will affect earlier as the symbol time T shortens, generating Inter-Symbol Interference (ISI). This has a main drawback, as ISI increases, more and more complex receiver side equalizers are required.
The main advantages of the parallelized DMT are clear: slower and therefore cheaper can be used and on the other hand, the symbols on the narrower subcarriers have longer durations, and they are less affected by distortions

due to impairments that increase with the symbol rate, as CD. The main drawback of DMT is also clearly shown in Figure 15. There is a loss in spectral efficiency as non-data-carrying spectral guard bands, Δf, are required to separate DMT subcarriers and avoid interferences from DMT subcarriers.

The main advantages of OFDM regarding DMT is that it eliminates the spectral guard bands, Δf, by setting a group of orthogonal sub-frequencies. Here orthogonality means that the interference, cross-talk, between the modulated sub-frequencies is eliminated. This is expressed as:

$$\int_0^T s_i(t)s_j(t)dt = 0 \qquad (1)$$

for any i ≠ j, where $s_i(t)$ represents each of the subcarrier frequency, f_i, for i = 0, 1, 2, …, N-1, modulated in general with a complex QAM symbol $A_i - A_i$, so that:

$$s_i(t) = A_i\cos(2\pi f_i t) - B_i\sin(2\pi f_i t) \qquad (2)$$

where the subcarrier frequencies, in order to satisfy Eq. (1), can be defined as integer multiples over the symbol time T as [97]:

$$f_i = \frac{i}{T} + f_{RF} \qquad (3)$$

where f_{RF} shows that the orthogonal set of subcarriers may also be upconverted to a Radio Frequency (RF), leading to discrete multitoned modulation for $f_{RF} \neq 0$. It can be shown by substituting f_i from Eq. (3) in expression (2), that each carrier $s_i(t)$ is orthogonal to each other $s_j(t)$, with i≠j, as defined by Eq. (1), and therefore, all the N OFDM subcarriers can occupy the same frequency spectrum, and partially overlap in frequency without interfering.

BW

f_{SC}

(a)

Δf

Guard band

f_0 f_1 f_2

(b)

$f_0 f_1 f_2$ f_{N-1}

(c)

Figure 15. Frequency-domain spectra for (a) Single Carrier (SC), (b) DMT, and (c) OFDM signals.

Therefore, the electrical OFDM signal can be expressed as:

$$s_{OFDM}(t) = \sum_{i=0}^{N-1} A_i\, g(t)\cos(2\pi f_i t) - B_i\, g(t)\sin(2\pi f_i t) \qquad (4)$$

were g(t) represents the impulse response of any selected baseband pulse shaping filter. E.g. a rectangular pulse described as g(t) = 1 if (0 ≤ t ≤T) and zero elsewhere, leading to the aggregate spectrum shown in Figure 16. It can be noticed that an implementation of OFDM by direct modulation of the N subcarriers, e.g. for N = 256, would require an array of N-1 synchronized analog oscillators both, at the transmitter and at the receiver. Fortunately, an alternative implementation of OFDM can be done digitally.

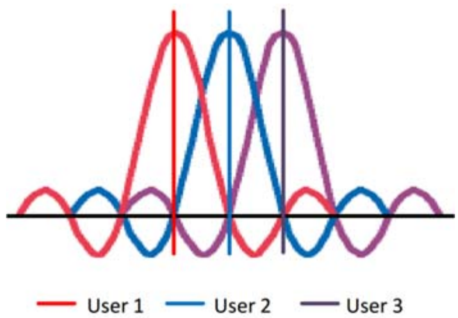


Figure 16. OFDM(A) spectrum with three orthogonal subcarriers.

The Eq. (4) can be rewritten as:

$$s_{OFDM}(t) = \Re\left\{e^{j2\pi f_{RF}t}\sum_{i=0}^{N-1}(A_i - jB_i)e^{j2\pi\frac{i}{T}t}\right\} \qquad (5)$$

so that, if the summation term of (5) can be generated efficiently, only one oscillator at f_{RF} is required. By sampling at times t=kT/N, for k = 1, 2, 3,… the summation term corresponds to the inverse discrete Fourier transform of a set of complex QAM symbols, $A_{n,k} - jB_{n,k}$, over N OFDM subcarriers. This can be implemented using the highly efficient Inverse Fast Fourier Transform (IFFT) algorithm.

As shown in Figure 17, the digital transmitter adds a Cyclic Prefix (CP) to the IFFT output, which is usually named the OFDM symbol.

The CP consist of a predefined tail-end of the OFDM symbol, which is introduced to its beginning, so that the OFDM symbol starts and ends in the same way, having this cyclic characteristic. The CP is introduced for reducing the Inter-Symbol-Interference (ISI) of the ODFM symbol and enabling Frequency-Domain Equalization (FDE). A tutorial explanation of the use and relevance of the use of CP can be followed in [97, 98]. As a short introduction just to say that due to dispersion of optical signals due fiber propagation, the OFDM symbol will be broaden. So long, the CP is at least as long as the dispersive delay of the channel, the CP will absorb the OFDM symbols spreading mitigating the ISI. Even more, thanks to the use of the CP, data symbols can be recovered

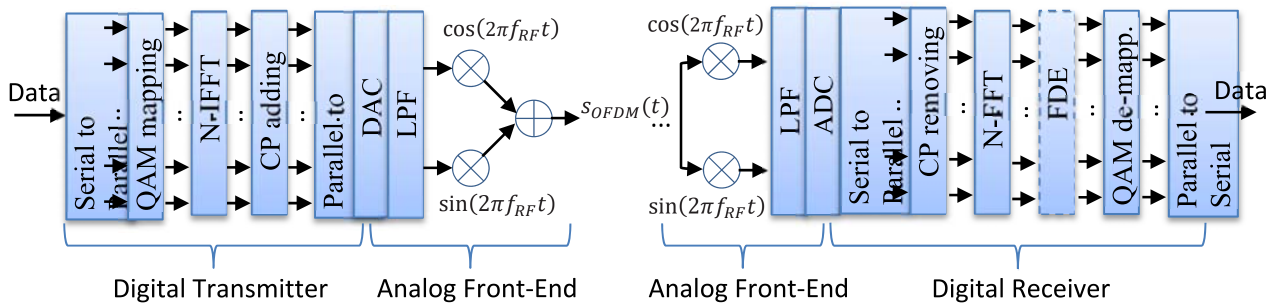


Figure 17. Block diagram for generic OFDM digital implementation.

by FDE (shown in dashed box at the digital receiver in Figure 17) requiring lower computational complexity than equivalent time-domain equalization algorithms [97]. The drawback of the CP is that it reduces the network transmitted data rate. Both SC and OFDM lead to natural application in multiuser PON access. As it has been discussed, the main advantage of OFDM is that a much more efficient use of the spectrum is obtain thanks to the orthogonality property of OFDM, so that an overlapping among the subcarriers is possible though with a reduced Inter Carrier Interference (ICI).

The main disadvantage of OFDM is the high Peak to Average Power Ratio (PAPR). The PAPR is due to the fact that the OFDM sinusoidal signals can sometimes add constructively in time domain, leading to sharp amplitude peaks, usually significantly larger than the average amplitude. This effect can stress RF amplifiers, as well as transmitter lasers, detectors, etc.; and it can make OFDM more vulnerable to optical fiber nonlinear impairments.

Applications of OFDM has been named Optical OFDM(A) or OFDM-Access and it has led to 3 main modulation/detection combinations [97]. They are: a) Intensity Modulation / Direct Detection (IM/DD), which is also referred as Optical-OFMD (O-OFDM); b) Optical modulation with coherent detection, also named as CO-OFDM; and c) all-optical filed modulation with coherent detection, also said as AO-OFDM.

The O-OFDM consist on modulating a Continuous Wave (CW) laser either by an Intensity Modulator (IM) or by an In-phase/Quadrature (I/Q) modulator for the conversion of the RF OFDM signal into the optical domain. Also a directly modulated laser can be also used [97]. The IM case, as optical intensity is a real, strictly non-negative quantity, the $s_{OFDM}(t)$ must be also real and positive. This can be achieved either by electrical I/Q signals multiplexing, or by providing a Hermitian (complex conjugate symmetrical) signal to the IFFT. The main advantage if Hermitian symmetry solution is that it avoids all practical difficulties derived from I/Q imbalances and imbalance compensation [97]. On the other hand, the disadvantage is that since Hermitian symmetry requires replacing half of the symbol frame with the complex conjugate of the first half, the total data rate is halved. Finally, to ensure that $s_{OFDM}(t)$ is positive, simply a sufficient large DC bias added to the $s_{OFDM}(t)$ is enough.

The O-OFDM is the most straight forward implementation; nevertheless, it faces significant impairments. For example, due to the requirement of a positive $s_{OFDM}(t)$, the O-OFDM signal will include a significant power at the optical carrier, thus increasing the vulnerability to Optical Signal-to-Noise-Ratio (OSNR) degradation. Also a significant Chromatic Dispersion (CD) is observed due to direct detection of a Double-Sideband (DSB) OFDM signal. Several techniques such as signal clipping and Optical Single-Side Band (OSSB) techniques have been introduced to minimize those effects [97].

Despite of the described difficulties, O-OFDM is a promising implementation of OFDM to PON and for example, adaptive 6.25 to 40 Gb/s has been achieved for downstream for transmission lengths from 0 to 100 km by four OFDM bands, using a MZM modulator, and 100 km transmission of 10Gb/s OFDM has been achieved by using a 2.5GHz DML [99].

Alternative solutions to overcome those limitations have been found by coherent detection, leading to Coherent Optical-OFDM (CO-OFDM) and All-Optical Field Modulation with Coherent Detection, also named as AO-OFDM. For interested readers on those advanced implementations of OFDM in PON, the very good tutorial on OFDM for Next-Generation Optical Access Networks is recommended [97]. On the other hand, due to the relevance of coherent detection and the future applications of this technology to PON, a brief introduction to this technique in recent implementations is given in next section.

Coherent Passive Optical Networks (PONs)

Coherent detection is a detection technique developed during 80's, having this name as it combines the incoming optical signal coherently with a CW optical field before arriving the detector [100]. Figure 18 shows the main elements of the basic implementation of a coherent detector.

Let's consider an incoming signal which electrical field can be expressed as:

$$E_S(t)\hat{e_S} = |A_S(t)|exp[j(\omega_S t + \theta_S(t))]\hat{e_S} \qquad (6)$$

and the electrical field of the local laser can be expressed as:

$$E_L(t)\widehat{e_L} = |A_L|exp\left[j\left(\omega_L t + \theta_L(t) - \frac{\pi}{2}\right)\right]\widehat{e_L} \quad (7)$$

where $\widehat{e_S}$ and $\widehat{e_L}$ represent the State Of Polarization (SOP) of the incoming signal and local laser, respectively; ω_S and ω_L represent the corresponding carrier frequencies; and $A_S(t) = |A_S(t)|\exp[j\theta_S(t)]$ and $A_L(t) = |A_L|\exp\left[j\left(\theta_L(t) - \frac{\pi}{2}\right)\right]$ represent the complex envelopes of the incoming signal and local laser. Please, note that $\theta_L(t)$ represents the phase noise of the local laser, while the intensity noise of the local laser [100] is neglected for this introduction.

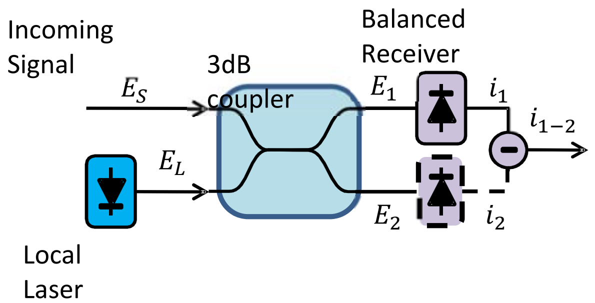


Figure 18. Scheme of a coherent receiver using a 3dB coupler as a 90° hybrid.

As shown in Figure 18, a device is required for coupling E_S and E_L. Though at early stages of coherent detectors a macroscopic beam splitter was proposed [100], nowadays, fiber couplers, widely used in PONs as basic passive device for distributing signal among the users are a wide common and cost-effective device for coherent devices. In particular, the simplest version of an ideal 3 dB coupler, dividing the input signals in two output signals without losses of equal amplitude 50% can be described as:

$$\begin{pmatrix} E_1 \\ E_2 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & j \\ j & 1 \end{pmatrix}\begin{pmatrix} E_S \\ E_L \end{pmatrix} \quad (8)$$

where the imaginary unit "j" as matrix coefficient indicates that the 3 dB coupler also acts as a 90° hybrid.
If the two detectors shown in Figure 18 are present, and they are very similar or ideally identical photodetectors, the difference between the two currents generated by both photodetectors, i_1 and i_2, leads to an electrical signal:

$$i_{1-2}(t) = R|A_S(t)|\,|A_L|\cos\left(\Delta\omega t + \Delta\theta_n + \theta_S(t)\right) \quad (9)$$

where $\Delta\omega$ stands for the frequency difference between both signals; $\Delta\theta_n$ stands for the phase difference due to phase noise of the signal and local laser; and assuming the same SOP for both optical fields. A more general expression can be found [100] for the case only one photodetector is present as indicated in Figure 18 by the dashed line of the second photodetector.
As it can be observed in Eq. (9), coherent receivers have several advantages as for example: a) the electrical signal is proportional to intensity of the local laser, providing a gain effect in the conversion from the optical signal $A_S(t)$ to the electrical signal; b) coherent detectors allows detecting the information of the complex envelope of the signal, both in amplitude of phase. Despite those advantages, a coherent detector implemented in the simplest configuration shown in Figure 18 shows some deficits as they are: a) the information transmitted at the amplitude and phase of the optical phase is coupled at the obtained electrical signal i_{1-2}; and on the other hand, b) the $\widehat{e_S}$ changes randomly inside most fiber links because of birefringence fluctuations related to environmental changes [100], leading to random changes in the quality of the received signal on a time scales ranging from seconds to microseconds [100].
Different schemes of coherent detectors have been developed to overcome the described main deficits. We introduce a relative standard more complex coherent scheme, providing: a) phase diversity; and b) polarization diversity, in Figure 19.

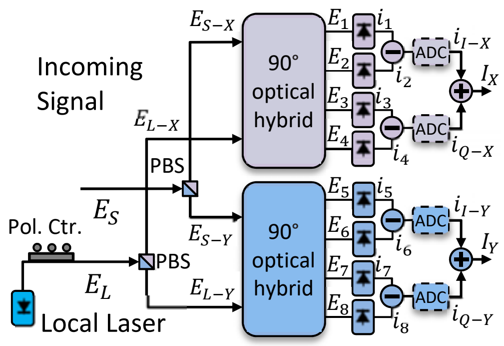


Figure 19. Scheme of a coherent 2×8 port receiver and 90° hybrids. PBS: Power Bean Splitter, Pol-Ctr: Polarization Controller.

As it can be seen in Figure 19, coherent receivers usually make use of digital techniques for many different porpoises as: static and dynamic channel equalization, interpolation and timing recovery, etc. Therefore, Analog to Digital Conversion (ADC) is required at some stage. In Figure 19 the ADC is marked in dashed lines at the output of the balanced detectors. For an extensive description of the digital algorithms and subsystems used in digital coherent optical receivers and their functionalities, please consult [101].
In the recent years, the coherent technology has started to become in a promising technology as a key enabler of the future access networks. Several research groups, including the previously described COCONUT project, have been working on these coherent technologies applied to the future access networks.
The future access networks will demand hard requirements to the optical technologies in order to fulfill higher data rates with longer and disparate user density Optical Distribution Networks (ODN). In addition, the new future access networks will be multiwavelength optical network, which will introduce new requirements to fulfill as colorless and tunable transceivers. In order to address these requirements, the coherent technologies have been proposed as the key enabler [102, 103].

In these recent years, cost-effective transceivers based on directly and externally modulated lasers has been studied and proposed in order to fulfill the sensitivity and data rate requirements [104-107]. In addition, simplified digital signal processing for optical coherent received signals has been researched and code modulation for the cost-effective transceivers has been developed [108-112]. Additionally, new receiver schemes have been researched for simplifying the optical and/or digital signal processing parts of the transceivers [113, 114]. Finally, new network approaches have been researched including extended metro-access networks with cost-effective ROADMs [115, 116], optical packet switching [117] and multicore fibers [118].

LIST OF ABBREVIATIONS

ADSL	Asymmetric DSL
AM	Amplitude Modulation
APD	Avalanche Photo-Diode
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
CAP	Carrierless Amplitude and Phase Modulation
CD	Chromatic Dispersion
CMTS	Cable Modem Termination System
CO	Central Office
CP	Cyclic Prefix
DBA	Dynamic Bandwidth Allocation
DFB	Distributed Feed-Back
DMT	Discrete Multitone Modulation
DSB	Double-Side-Band
DPSK	Differential Phase Shift Keying
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DOCSIS	Data Over Cable Service Interface Specification
EAM	Electro-Absorption Modulator
EDF	Erbium Doped fiber
EDFA	Erbium Doped Fiber Amplifier
FC	Fiber Channel
FDD	Frequency Division Duplex
FDE	Frequency-Domain Equalization
FDM	Frequency Division Multiplexed
FSAN	Full Service Access Network
FTTX	Fiber-To-The-X
HDSL	high data rate DSL
IAD	Integrated Access Device
ICI	Inter Carrier Interference
IDSL	ISDN Digital Subscriber Line
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
ISDN	integrated services digital network
ISI	Inter-Symbol Interference
ITU	International Telecommunication Union
LR	Long Reach
MMA	Multi-Modulus Algorithm
MOEMS	Micro-Opto-Electro-Mechanical System
MSDSL	Multirate Symmetric DSL
MSO	Multiple Service Operator
MZM	Mach Zehnder Modulator
NP	Network Provider
NRZ	Non-Return-To-Zero
NTSC	North American National Television System Committee
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OOK	On-Off-Keying
ONT	Optical Network Terminal
ONU	Optical Network Unit
OLT	Optical Line Terminal
OSNR	Optical Signal-To-Noise-Ratio
OSSB	Optical Single-Side Band
P2P	Point-To-Point
P2MP	Point-To-Multi-Point
PAPR	Peak to Average Power Ratio
PBX	Private Branch Exchange
PIP	Physical Infrastructure Providers
PON	Passive Optical Network
POTS	Plain Old Telephone Service
RADSL	Rate Adaptive DSL
RF	Radio Frequency
RMI	Reduced Modulation Index
RN	Remote Node
SDSL	Symmetric DSL
SP	Services Provider
SOA	Semiconductor Optical Amplifier
SSMF	Standard Single Mode Fiber
TCO	Total Cost of Ownership
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TS1	Transmission System 1
UMTS	Universal Mobile Telecommunications System
US	United States
VDSL	Very High Data Rate DSL
VOD	Video-On-Demand
VSB	Vestigial Side Band
WDM	Wavelength Division Multiplexing
WiMAX	Worldwide Interoperability for Microwave Access

BIBLIOGRAPHY

1. Lam, C. F. (Ed.). (2011). Passive optical networks: principles and practice. Academic Press.
2. Kleinrock, L. (1991). ISDN-The path to broadband networks. Proceedings of the IEEE, 79(2), 112-117.
3. SECTOR, S., & ITU, O. SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS International telephone connections and circuits–General definitions.
4. Golden, P., Dedieu, H., & Jacobsen, K. S. (Eds.). (2005). Fundamentals of DSL technology. CRC Press.

5. Curt Franklin "How DSL Works" 7 August 2000. HowStuffWorks.com.
6. Keiser, G. (2006). FTTX concepts and applications (Vol. 91). John Wiley & Sons.
7. Bingham, J. A. (2000). ADSL, VDSL, and multicarrier modulation (p. p45). New York: Wiley.
8. Federal Communications Commission, Telecommunications Act of 1996, available from http://www.fcc.gov/Reports/tcom1996.pdf.
9. Cable Labs, Data Over Cable Service Interface Specification (DOCSIS), available from http://www.cablemodem.com/specifications
10. Jordanova, L., & Dobrev, D. (2012). Improvement of the CATV Coaxial Distribution System Parameters. International Journal of Computer Science and Network Security (IJCSNS), 12(5), 123.
11. Proakis, J. G., Salehi, M., Zhou, N., & Li, X. (1994). Communication systems engineering (Vol. 94). New Jersey: Prentice Hall.
12. Effenberger, F., Cleary, D., Haran, O., Kramer, G., Li, R. D., Oron, M., & Pfeiffer, T. (2007). An introduction to PON technologies [Topics in Optical Communications]. IEEE Communications Magazine, 45(3), S17-S25.
13. Eklund, C., Marks, R. B., Stanwood, K. L., & Wang, S. (2002). IEEE standard 802.16: a technical overview of the WirelessMAN™ air interface for broadband wireless access. IEEE communications magazine, 40(6), 98-107.
14. Xiao, Y. (2005). Energy saving mechanism in the IEEE 802.16e wireless MAN.IEEE Communications Letters, 9(7), 595-597.
15. Prasad, R. (2004). OFDM for wireless communications systems. Artech House.
16. Zhang, Li, and Pengfei Sun. Introduction to OFDMA. Orthogonal Frequency Division Multiple Access Fundamentals and Applications (2010): 1.
17. Universal Mobile Telecommunications System (UMTS), UTRAN Overall Description, 3GPP TS 25.401.
18. Lempiäinen, Jukka, and Matti Manninen. UMTS radio network planning, optimization and QoS management. Dodrecht Kluwer Academic Publishers (2003).
19. Lee, Jhong Sam, and Leonard E. Miller. CDMA systems engineering handbook. Artech House, Inc., 1998.
20. Wagner, S. S., Kobrinski, H., Robe, T. J., Lemberg, H. L., & Smoot, L. S. (1988). Experimental demonstration of a passive optical subscriber loop architecture. Electronics Letters, 24(6), 344-346.
21. Wagner, S. S., & Lemberg, H. L. (1989). Technology and system issues for the WDM-based fiber loop architecture. Journal of Lightwave Technology, 7(11), 1759-1768.
22. Frigo, N. J., Iannone, P. P., & Reichmann, K. C. (2004). A view of fiber to the home economics. IEEE communications Magazine, 42(8), S16-S23.
23. Kim, K. S. (2003). On the evolution of PON-based FTTH solutions. Information sciences, 149(1), 21-30.
24. Mukherjee, B. (2006). Optical WDM networks. Springer Science & Business Media.
25. Frigo, N. J. (1997). A survey of fiber optics in local access architectures. Opt. Fiber Telecommun, 461-522.
26. Banerjee, A., Park, Y., Clarke, F., Song, H., Yang, S., Kramer, G., ... & Mukherjee, B. (2005). Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review [Invited]. Journal of optical networking, 4(11), 737-758.m).
27. Grobe, Klaus, and Jorg-Peter Elbers. "PON in adolescence: from TDMA to WDM-PON." IEEE Communications Magazine 46.1 (2008).
28. Krammer G., (2005) Ethernet Passive Optical Networks, McGraw-Hill, New York, USA.
29. International Telecommunication Union Telecommunication (ITU-T) 2005, Broadband optical access systems based on Passive Optical Networks (PON), G.983.1, International Telecommunication Union Telecommunication (ITU-T).
30. International Telecommunication Union Telecommunication (ITU-T) 2005, ONT management and control interface specification for B-PON, G.983.2, International Telecommunication Union Telecommunication (ITU-T).
31. International Telecommunication Union Telecommunication (ITU-T) 2002, A broadband optical access system with increased service capability by wavelength allocation, G.983.3, International Telecommunication Union Telecommunication (ITU-T).
32. International Telecommunication Union Telecommunication (ITU-T) 2001, A broadband optical access system with increased service capability using dynamic bandwidth assignment, G.983.4, International Telecommunication Union Telecommunication (ITU-T).
33. International Telecommunication Union Telecommunication (ITU-T) 2002, A broadband optical access system with enhanced survivability, G.983.5, International Telecommunication Union Telecommunication (ITU-T).
34. Lam, C., (2007) Passive Optical Networks, Elsevier, San Diego, USA.
35. Qiu, X., "Burst-mode Receiver Technology for Short Synchronization," Proceedings of Optical Fiber Communication Conference 2013 (OFC 2013), Anaheim, USA, paper OW3G.4.
36. International Telecommunication Union Telecommunication (ITU-T) 2008, Gigabit-capable passive optical networks (G-PON): General characteristics, G.984.1, International Telecommunication Union Telecommunication (ITU-T).
37. International Telecommunication Union Telecommunication (ITU-T) 2003, Gigabit-capable Passive Optical Networks (G-PON): Physical Media Dependent (PMD) layer specification, G.984.2, International Telecommunication Union Telecommunication (ITU-T).
38. International Telecommunication Union Telecommunication (ITU-T) 2014, Gigabit-capable passive optical networks (G-PON): Transmission convergence layer specification, G.984.3, International Telecommunication Union Telecommunication (ITU-T).
39. International Telecommunication Union Telecommunication (ITU-T) 2014, Gigabit-capable passive optical networks (G-PON): ONT management and control interface specification, G.984.4, International Telecommunication Union Telecommunication (ITU-T).
40. International Telecommunication Union Telecommunication (ITU-T) 2014, Gigabit-capable passive optical networks (G-PON): Enhancement band, G.984.5, International Telecommunication Union Telecommunication (ITU-T).
41. International Telecommunication Union Telecommunication (ITU-T) 2008, Gigabit-capable passive optical networks (G-PON): Reach extension, G.984.6, International Telecommunication Union Telecommunication (ITU-T).

42. International Telecommunication Union Telecommunication (ITU-T) 2010, Gigabit-capable passive optical networks (G-PON): Long reach, G.984.7, International Telecommunication Union Telecommunication (ITU-T).

43. Kani, J., "Standardization of Optical Access Technologies: Progress and Future Prospects," Proceedings of OptoElectronics and Communications Conference/ Photonics in Switching 2016 (OECC/PS 2016), Niigata, Japan, paper TuA3-2.

44. International Telecommunication Union Telecommunication (ITU-T) 2012, 10-Gigabit-capable passive optical network (XG-PON) systems: Definitions, abbreviations and acronyms, G.987, International Telecommunication Union Telecommunication (ITU-T).

45. International Telecommunication Union Telecommunication (ITU-T) 2016, 10-Gigabit-capable passive optical networks (XG-PON): General requirements, G.987.1, International Telecommunication Union Telecommunication (ITU-T).

46. International Telecommunication Union Telecommunication (ITU-T) 2016, 10-Gigabit-capable passive optical networks (XG-PON): Physical media dependent (PMD) layer specification, G.987.2, International Telecommunication Union Telecommunication (ITU-T).

47. International Telecommunication Union Telecommunication (ITU-T) 2014, 10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification, G.987.3, International Telecommunication Union Telecommunication (ITU-T).

48. International Telecommunication Union Telecommunication (ITU-T) 2014, 10-Gigabit-capable passive optical networks (XG-PON): Reach extension, G.987.4, International Telecommunication Union Telecommunication (ITU-T).

49. International Telecommunication Union Telecommunication (ITU-T) 2012, ONU management and control interface (OMCI) specification, G.988, International Telecommunication Union Telecommunication (ITU-T).

50. Elbers, J. and Grobe, K., Optical Access Solutions beyond 10GEPON/XGPON, Proceedings of Optical Fiber Communication Conference 2010 (OFC 2010), San Diego, USA, paper OTuO1.

51. Effenberger, F.J., The XG-PON System: Cost Effective 10 Gb/s Access, J. Lightwave Technol. 29, 403-409 (2011).

52. International Telecommunication Union Telecommunication (ITU-T) 2015, 40-Gigabit-capable passive optical networks (NG-PON2): Definitions, abbreviations and acronyms, G.989, International Telecommunication Union Telecommunication (ITU-T).

53. International Telecommunication Union Telecommunication (ITU-T) 2016, 40-Gigabit-capable passive optical networks (NG-PON2): General requirements, G.989.1, International Telecommunication Union Telecommunication (ITU-T).

54. International Telecommunication Union Telecommunication (ITU-T) 2014, 40-Gigabit-capable passive optical networks 2 (NG-PON2): Physical media dependent (PMD) layer specification, G.988.2, International Telecommunication Union Telecommunication (ITU-T).

55. International Telecommunication Union Telecommunication (ITU-T) 2015, 40-Gigabit-capable passive optical networks (NG-PON2): Transmission convergence layer specification, G.989.3, International Telecommunication Union Telecommunication (ITU-T).

56. Wey, J.S., Nesset, D., Valvo, M., Grobe, K., Roberts, H., Luo, Y., and Smith, J., Physical Layer Aspects of NG-PON2 Standards—Part 1: Optical Link Design [Invited], J. Opt. Commun. Netw. 8, 33-42 (2016).

57. Luo, Y., Roberts, H., Grobe, K., Valvo, M., Nesset, D., Asaka, K., Rohde, H., Smith, J., Wey, J.S., and Effenberger, F., Physical Layer Aspects of NG-PON2 Standards—Part 2: System Design and Technology Feasibility [Invited], J. Opt. Commun. Netw. 8, 43-52 (2016).

58. Nesset, D., NG-PON2 Technology and Standards, J. Lightwave Technol. 33, 1136-1143 (2015).

59. F. Effenberger, XG-PON1 versus NG-PON2: which one will win?, ECOC 2012, paper Tu.4.B.1.

60. International Telecommunication Union Telecommunication (ITU-T) 2016, 10-Gigabit-capable symmetric passive optical network (XGS-PON), G.9807.1, International Telecommunication Union Telecommunication (ITU-T).

61. International Telecommunication Union Telecommunication (ITU-T) 2016, 10-Gigabit-capable symmetric passive optical network (XGS-PON), G.9807.1, International Telecommunication Union Telecommunication (ITU-T). Institute of Electrical and Electronics Engineers (IEEE) 2004, Media Access Control Parameters, Physical Layers, and Management Parameters for Subscriber Access Networks, IEEE Std 802.3ah-2004, Institute of Electrical and Electronics Engineers (IEEE).

62. Institute of Electrical and Electronics Engineers (IEEE) 2009, Physical Layer Specifications and Management Parameters for 10 Gb/s Passive Optical Networks, IEEE Std 802.3av-2009, Institute of Electrical and Electronics Engineers (IEEE).

63. Hajduczenia, M., Inácio, P.R.M., da Silva, H.J.A., Freire, M.M., and Monteiro, P.P., 10G EPON Standardization in the Scope of IEEE 802.3av Project, Proceedings of Optical Fiber Communication Conference 2008 (OFC 2008), San Diego, USA, paper NMD4.

64. Tanaka, K., Agata, A., and Horiuchi, Y., IEEE 802.3av 10G-EPON Standardization and Its Research and Development Status, J. Lightwave Technol. 28, 651-661 (2010).

65. Chen, C., Chair, Z., and Velmurugan, B., 10G EPON: Next Generation Ethernet Passive Optical Networks, Proceedings of Optical Fiber Communication Conference 2009 (OFC 2009), San Diego, USA, paper JThA80.

66. Institute of Electrical and Electronics Engineers (IEEE) 2015, IEEE 802.3 Industry Connections Feasibility Assessments for the Next Generation of EPON.

67. Knitte, C. 2016, IEEE 100Gb/s EPON, Proceedings of Optical Fiber Communication Conference 2016 (OFC 2016), Anaheim, USA, paper Th1I.6.

68. Marco Ruffini, Lena Wosinska, Mohand Achouche, Jiajia Chen, Nick Doran, Farsheed Farjady, Julio Montalvo, Peter Ossieur, Barry O'Sullivan, Nick Parsons, Thomas Pfeiffer, Xing-Zhi Qiu, Christian Raack, Harald Rohde, Marco Schiano, Paul Townsend, Roland Wessaly, Xin Yin, David B. Payne, DISCUS: an end-to-end solution for ubiquitous broadband optical access, IEEE Communications Magazine, vol. 52, no. 2, pp. S24-S32, February 2014.

69. M. Ruffini, M. Achouche, A. Arbelaez, R. Bonk, A. Di Giglio, N. J. Doran, M. Furdek, R. Jensen, J. Montalvo, N. Parsons, T. Pfeiffer, L. Quesada, C. Raack, H. Rohde, M. Schiano, G.

Talli, P. Townsend, R. Wessaly, L. Wosinska, X. Yin, D. B. Payne, Access and metro network convergence for flexible end-to-end network design [invited], in IEEE/OSA Journal of Optical Communications and Networking, vol. 9, no. 6, pp. 524-535, June 2017.

70. Giuseppe Talli, Frank Slyne, Stefano Porto, Daniel Carey, Nicola Brandonisio, Alan Naughton, Peter Ossieur, Seamas McGettrick, Christian Blümm, Marco Ruffini, David Payne, Rene Bonk, Thomas Pfeiffer, Nick Parsons, Paul Townsend, SDN Enabled Dynamically Reconfigurable High Capacity Optical Access Architecture for Converged Services, in Journal of Lightwave Technology, vol. 35, no. 3, pp. 550-560, Feb.1, 1 2017.

71. J. A. Lazaro, V. Polo, C. Bock, M. Omella and J. Prat, Remotely Amplified SARDANA: Single-fibre-tree Advanced Ring-based Dense Access Network Architecture, 2006 European Conference on Optical Communications, Cannes, France, 2006, pp. 1-2.

72. Ana Lovrić, Slaviša Aleksić, Jose A. Lazaro, Giorgio M. Tosi Beleffi, Francesc Bonada, Josep Prat, Antonio L. J. Teixeira, Influence of broadcast traffic on energy efficiency of long-reach SARDANA access network, 2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference, Los Angeles, CA, 2011, pp. 1-3.

73. Bernhard Schrenk, Jose A. Lazaro, Dimitrios Klonidis, Francesc Bonada, Fabienne Saliou, Victor Polo, Eduardo Lopez, Quang T. Le, Philippe Chanclou, Liliana Costa, Antonio Teixeira, Sotiria Chatzi, Ioannis Tomkos, Giorgio M. Tosi Beleffi, Dmitri Leino, Risto Soila, Spiros Spirou, Guilhem de Valicourt, Romain Brenot, Christophe Kazmierski, Josep Prat, Demonstration of a Remotely Dual-Pumped Long-Reach PON for Flexible Deployment, in Journal of Lightwave Technology, vol. 30, no. 7, pp. 953-961, April1, 2012.

74. J. A. Lazaro, R. I. Martinez, V. Polo, C. Arellano and J. Prat, Hybrid Dual-fiber-Ring with Single-fiber-Trees Dense Access Network Architecture using RSOA-ONU, OFC/NFOEC 2007 - 2007 Conference on Optical Fiber Communication and the National Fiber Optic Engineers Conference, Anaheim, CA, 2007, pp. 1-3.

75. Giuseppe Talli, Chi Wai Chow, Paul Townsend, Russell Davey, Tine De Ridder, Xing-Zhi Qiu, Peter Ossieur, Heinz-Georg Krimmel, David Smith, Ian Lealman, Alistair Poustie, Sebastian Randel, Harald Rohde, Integrated Metro and Access Network: PIEMAN, NOC (12th European Conference on Networks & Optical Communications), Stockholm; Sweden, 2007, pp. 493-500

76. S. Smolorz, H. Rohde, P. Ossieur, C. Antony, P. D. Townsend, T. De Ridder, B. Baekelandt, X. Z. Qiu, S. Appathurai, H. -G. Krimmel, D. Smith, A. Poustie, Next generation access networks: PIEMAN and beyond, 2009 International Conference on Photonics in Switching, Pisa, 2009, pp. 1-4.

77. Gemma Vall-llosera, Albert Rafel, Neil Parkin, Marianna Angelou, Dimitrios Klonidis, Ivan Cano, Marco Presi, George Papastergiou, Ioannis Tomkos, Josep Prat, Ernesto Ciaramella, COCONUT cost, power consumption and migration analysis: A route towards NG-PON3, 2015 17th International Conference on Transparent Optical Networks (ICTON), Budapest, 2015, pp. 1-4.

78. M. Artiglia, R. Corsini, M. Presi, F. Bottoni, G. Cossu and E. Ciaramella, Coherent Systems for Low-Cost 10 Gb/s Optical Access Networks, in Journal of Lightwave Technology, vol. 33, no. 15, pp. 3338-3344, Aug.1, 1 2015.

79. I. Cano, A. Lerín, V. Polo, and J. Prat, Simplified polarization diversity heterodyne receiver for 1.25Gb/s cost-effective udWDM-PON, in Proc. OFC 2014, paper W4G.3.

80. K. Prince, T. B. Gibbon, R. Rodes, E. Hviid, C. I. Mikkelsen, C. Neumeyr, M. Ortsiefer, E. Ronneberg, J. Rosskopf, P. Ohlen, E. I. de Betou, B. Stoltz, E. Goobar, J. Olsson, R. Fletcher, C. Abbott, M. Rask, N. Plappert, G. Vollrath, and I. T. Monroy, GigaWaMNext-generation WDMPON enabling gigabit per-user data bandwidth, J. Lightw. Technol., vol. 30, no. 10, pp. 1444–1454, May 2012.

81. Olmedo, Miguel Iglesias, et al. Gigabit Access Passive Optical Network Using Wavelength Division Multiplexing—GigaWaM. Journal of Lightwave Technology 32.22 (2014): 3683-3691.

82. Forzati, M., Bianchi, A., Chen, J., Grobe, K., Lannoo, B., Machuca, C. M., ... & Wosinska, L. (2015). Next-generation optical access seamless evolution: Concluding results of the European FP7 project OASE. Journal of Optical Communications and Networking, 7(2), 109-123

83. Wang, K., Machuca, C. M., Wosinska, L., Urban, P. J., Gavler, A., Brunnström, K., & Chen, J. (2017). Techno-economic analysis of active optical network migration toward next-generation optical access. Journal of Optical Communications and Networking, 9(4), 327-341

84. Mahloo, M., Machuca, C. M., Chen, J., & Wosinska, L. (2013). Protection cost evaluation of WDM-based next generation optical access networks. Optical Switching and Networking, 10(1), 89-99.

85. Konstantinos Kanonakis, Ioannis Tomkos, Heinz-George Krimmel, Frank Schaich, Christoph Lange, Erik Weis, Juerg Leuthold, Marcus Winter, Sergio Romero, Pandelis Kourtessis, Milos Milosavljevic, Ivan N. Cano, Josep Prat, An OFDMA-based optical access network architecture.

86. Jinlong Wei, Nicklas Eiselt, Christian Sanchez, Ruoyang Du, and Helmut Griesser, 56Gb/s multi-band CAP for data center interconnects up to an 80km SMF, Opt. Lett. 41, 4122-4125 (2016).

87. B. Schrenk and M. Stierle, Split extension beyond 1:1000 for fully-passive coherent PONs with infrastructure-defined self-amplification, 2014 16th International Conference on Transparent Optical Networks (ICTON), Graz, 2014.

88. B. Schrenk et al., Low-cost transmitter for flexible-format generation up to 16-QAM for spectral-efficiency conscious PONs, 39th European Conference and Exhibition on Optical Communication (ECOC 2013), London, 2013.

89. B. Schrenk, Roland Lieger, Thomas Lorünser, Paraskevas Bakopoulos, Andreas Poppe, Martin Stierle, Hercules Avramopoulos, and Helmut Leopold, Fully Passive Resiliency Node for Optical Access [Invited], J. Opt. Commun. Netw. 7, B10-B15 (2015).

90. Y. Ma, et al, “Demonstration of a 40Gb/s time and Wavelength Division Multiplexed passive optical network prototype system,” in Optical Fiber Communication Conference 2012, paper PDP5D.7

91. Houtsma, V., van Veen, D., & Harstead, E. (2017). Recent Progress on Standardization of Next-Generation 25, 50, and 100G EPON. Journal of Lightwave Technology, 35(6), 1228-1234.

92. Winzer, P. J., & Essiambre, R. J. (2006). Advanced optical modulation formats. Proceedings of the IEEE, 94(5), 952-985.

93. Lach, E., & Idler, W. (2011). Modulation formats for 100G and beyond. Optical Fiber Technology, 17(5), 377-386.

94. Chow, C. W., & Yeh, C. H. (2010). 40-Gb/s downstream DPSK and 40-Gb/s upstream OOK signal remodulation PON using reduced modulation index. Optics express, 18(25), 26046-26051.

95. A. H. Gnauck and P. J. Winzer, Optical phase-shift-keyed transmission, J. Lightw. Technol., vol. 23, no. 1, pp. 115–130, Jan. 2005.

96. G. Charlet, E. Corbel, J. Lazaro, A. Klekamp, R. Dischler, P. Tran, W. Idler, H. Mardoyan, A. Konczykowska, F. Jorge, and S. Bigo, WDM transmission at 6-Tbit/s capacity over transatlantic distance, using 42.7-Gb/s differential phase-shift keying without pulse carver, J. Lightw. Technol., vol. 23, no. 1, pp. 104–107, Jan. 2005.

97. Cvijetic, N. OFDM for next-generation optical access networks. Journal of lightwave technology, 30(4), 384-398 (2012).

98. N. Cvijetic, OFDM in optical access networks, OFC, paper OMG3).

99. C. H. Yeh, et al, Using adaptive four-band OFDM modulation with 40 Gb/s downstream and 10 Gb/s upstream signals for next generation long-reach PON, Opt. Express, vol. 19, pp. 26150-26160, 2011

100. Agrawal, Govind P. Fiber-optic communication systems. Vol. 222. John Wiley & Sons, 2012.

101. Savory, S. J. (2010). Digital coherent optical receivers: Algorithms and subsystems. IEEE Journal of Selected Topics in Quantum Electronics, 16(5), 1164-1179.

102. H. Rohde, S. Smolorz, J. S. Wey and E. Gottwald, Coherent optical access networks, 2011 Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference, Los Angeles, CA, 2011, pp. 1-3.

103. A. Shahpari et al., Coherent Access: A Review, in Journal of Lightwave Technology, vol. 35, no. 4, pp. 1050-1058, Feb.15, 15 2017.

104. J.A. Altabas, D. Izquierdo, J.A. Lazaro, A. Lerin, F. Sotelo, and I Garces, 1Gbps full-duplex links for ultra-dense-WDM 6.25GHz frequency slots in optical metro-access networks, Opt. Express 24, 555-565 (2016)

105. J.A. Altabas, D. Izquierdo, J.A. Lazaro and I. Garces, Cost-Effective Transceiver Based on an RSOA and a VCSEL for Flexible uDWDM Networks, in IEEE Photonics Technology Letters, vol. 28, no. 10, pp. 1111-1114, May15, 15 2016.

106. J. A. Altabas, D. Izquierdo, J. A. Lazaro, and I. Garces, 1.25-2.5Gbps Cost-Effective Transceiver Based on Directly Phase Modulated VCSEL for Flexible Access Networks, in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2017), paper Th1K.4.

107. J.A. Altabas, D. Izquierdo, J.A. Lazaro, and I. Garces, Chirp-based direct phase modulation of VCSELs for cost-effective transceivers, Opt. Lett. 42, 583-586 (2017)

108. S. J. Savory, Digital coherent optical access networks, 2013 IEEE Photonics Conference, Bellevue, WA, 2013, pp. 125-126.

109. D. Lavery, R. Maher, D.S. Millar, B.C. Thomsen, P. Bayvel, and S.J. Savory, Digital Coherent Receivers for Long-Reach Optical Access Networks, J. Lightwave Technol. 31, 609-620 (2013)

110. K. Matsuda, R. Matsumoto, N. Suzuki, Hardware-efficient Adaptive Equalization and Carrier Phase Recovery for 100 Gb/s/λ-based Coherent WDM-PON Systems, in European Conference on Optical Communication, Gothenburg, Sweden, 2017, paper, Th.1.B.2

111. L. Lundberg, M. Mazur, A. Lorences-Riesgo, M. Karlsson, P. Andrekson, Joint Carrier Recovery for DSP Complexity Reduction, in Frequency Comb-Based Superchannel Transceivers.

112. M.S. Erkılınç et al., Polarization-Insensitive Single-Balanced Photodiode Coherent Receiver for Long-Reach WDM-PONs , in Journal of Lightwave Technology, vol. 34, no. 8, pp. 2034-2041, April15, 15 2016.

113. S. Ziaie et al., Adaptive stokes space based polarization demultiplexing for flexible UDWDM metro-access networks, 2017 Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, CA, 2017, pp. 1-3.

114. I. Molina-Fernandez et al., Coherent receivers for demanding applications, 2016 Optical Fiber Communications Conference and Exhibition (OFC), Anaheim, CA, 2016, pp. 1-3.

115. S. Sarmiento, S. Spadaro and J.A. Lazaro, Cost-effective ROADM architecture for C/DWDM Metro-Access Networks convergence, 2017 19th International Conference on Transparent Optical Networks (ICTON), Girona, 2017, pp. 1-4.

116. Sarmiento, S., Spadaro, S. Lazaro, J. A. Cost-effective DWDM ROADM Design for Flexible Sustainable Optical Metro-Access Networks, Journal of Optical Communications and Networking (JOCN), IEEE, Accepted Paper for Publication, October, 2017.

117. J. M. D. Mendinueta, S. Shinada, H. Furukawa and N. Wada, Ultra-high-capacity optical packet switching networks with coherent polarization division multiplexing modulation formats and related technologies, 2017 19th International Conference on Transparent Optical Networks (ICTON), Girona, 2017, pp. 1-4.

118. Z. Feng et al., Large-capacity optical access network utilizing multicore fiber and self-homodyne coherent detection, 2017 Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, CA, 2017, pp. 1-3.

JOSE A. ALTABAS
SAMAEL SARMIENTO
JOSE A. LAZARO

Universitat Politècnica de Catalunya, Spain