X

Next Generation Optical Access Networks: from TDM to WDM

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1. Introduction

Network infrastructure plays a key role in the success of added services and in user satisfaction. It is widely accepted that Passive Optical Networks (PON) are the most promising, cost-effective, and high-performance access network solutions. Access networks are also commonly referred to as either 'the last mile' by the operators, or 'the first mile of the network' in IEEE terminology. The term 'mile' is often related to the path portion that is used to reach the user from a network node, however access networks go as far as 20 km depending on the technology used.

An access network comprises connections between different subscribers and a Central Office (CO), which is attached to the metro or core network. The wired technology deployed varies significantly from one country to another, i.e. Digital Subscriber line (xDSL), based on copper wires; Hybrid Fiber-coax (HFC), and optical fiber.

The trends for Next Generation Access Networks (NGA) based on PON are: Wavelength Division Multiplexing (WDM), 10 Gb/s or more, and longer reach/higher splits. NGA must be able to cope with challenges, such as delivering diverse broadband services and facilitating the integration of different technologies. Moreover, NGA should provide higher bandwidths or further reduce the cost of existing delivering services, and serve as backhaul of wireless access networks (WiFi, WiMAX). The last one constitutes a relevant issue for the convergence between wireless and wired technologies.

1.1 Optical access networks - Fiber-to-the –x

Single-mode fiber's properties, such as low loss and extremely wide inherent bandwidth, make it the ideal candidate to meet the capacity challenges for today's and for the foreseeable future. This kind of fiber is often used in core and metropolitan networks, and nowadays their penetration in the access domain is increasing as well (Koonen, 2006).

The Passive Optical Network (PON) is the most interesting solution, basically because there is no active equipment installed in the field – a very satisfying feature for incumbent operators, and also because the equipment and the feeder fibers are shared amongst users.

The application of PON technology to provide broadband connectivity to subscribers in the access network is called fiber–to-the-x (FTTx). Depending on how deep the fiber penetrates

into the first mile, FTTx can be classified as: FTTB (Business/Building), FTTC/Cab (Curb/Cabinet), FTTN (Neighborhood/Node), FTTP (Premises), and FTTH (Home). There is no final agreement in the terminology to be used all over the world, but the most common terms in the market are: FTTN/B and FTTH. The FTTN/B describes a PON where the fiber arrives directly from the CO to the building (or business premises) and the signal is converted and carried to the user dependencies by using copper or coaxial cables. Figure 1 depicts a FTTN/B, where the optical signal is converted to electrical signal in the very last mile of the network, and then is carried by means of a vDSL network up to the subscriber's premises.
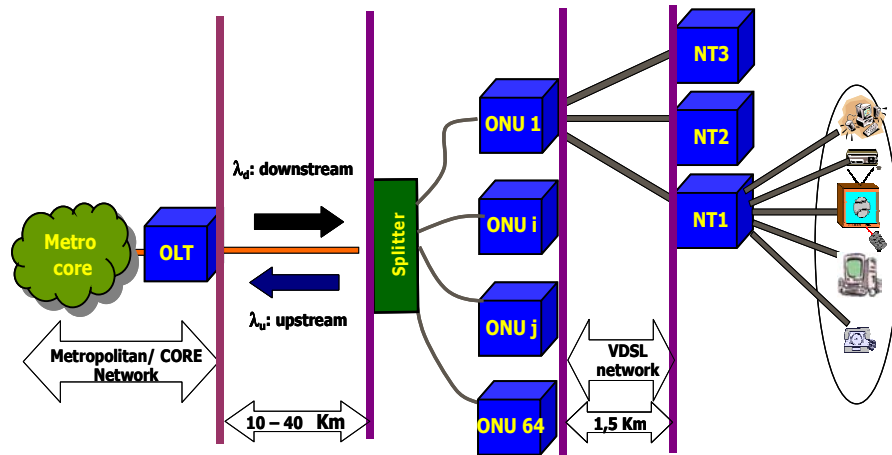

Fig. 1 FTTN/B network

FTTH refers to the reach of the fiber wire till the subscriber premises. It consists of an Optical Line Termination (OLT) at the service provider's CO, and a number of terminals near the end-user's device called Optical Network Unit (ONU) or Optical Network Terminal (ONT). PON can use single or multiple fibers for upstream and downstream traffic, with or without WDM, being a single fiber-single channel tree the most common topology [Figure 1].

The downstream channel is a broadcast channel, and the upstream channel is often shared amongst users' devices – their access must be arbitrated in order to avoid collisions amongst stations. Each ONU transmits a burst of data that cannot be interfered by any other burst sent from another ONU. For that reason, users' bursts are separated by a configurable guard-time. Such single full-duplex channel-single fiber solutions are commonly referred to as TDM-PON.

The worldwide market reflected that, by the end of 2008, PON networks, mainly FTTB/N and FTTH, were deployed on a large scale in Asia (78.5%) - APAC countries - and North America (13.5%). The market in Europe was far behind that of the APAC countries or America, scoring about 8%. However, there are many initiatives that aim to deploy PON networks all around and it is expected that such deployment will even grow faster in a short period of time in Europe. (Lakic & Hajduczenia, 2007).

2. Legacy TDM-PON

Two main FTTH-PON standards are currently deployed around the world: Ethernet-based PON (EPON), approved in 2004 (IEEE 802.3ah, 2004); and Gigabit-capable PON (GPON), born in 2003 (ITU-T G.984.[1-4], 2003). In both solutions, the equipment installed in the field is fully passive, covering distances of up to 20 km, using a point-to-multipoint topology, providing wider bandwidth to the end user, and allowing video broadcasting (digital and/or analogue). The split-ratio (users per fiber) is variable – commonly, an average of 32 to 64 users.

In fact, the basic physical features for both standards are very similar – what makes them more different is the MAC protocol and the data encapsulation scheme. While EPON carries bursts of pure Ethernet frames, GPON encapsulates data using Generic Encapsulation Method (GEM). Fair and efficient bandwidth allocation to users is a key issue that is out of the scope of the standards.

2.1 The EPON standard: IEEE 802.3ah - Ethernet in the First Mile

The EPON is a point-to-multipoint network, whose topology is basically a single fiber-single channel tree. The bit rate is symmetric, up to 1 Gb/s – therefore, the maximum bandwidth allocated to each ONU is typically around 70 Mb/s, though it depends on the number of active ONUs and the users' traffic profiles. The EPON standard focuses on defining the physical and the MAC layer as shown in Figure 2. In (Kramer, 2005) the author explains such standard deeply.
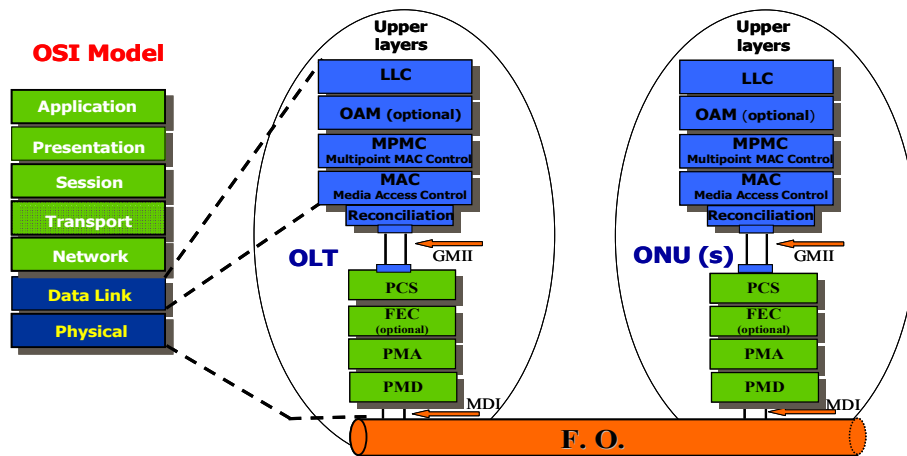

Fig. 2 architecture model of an EPON

Ethernet frames cannot be segmented before their transmission in an EPON. Therefore, the transmission of a frame will be deferred to the next cycle in case it does not fit in the current assigned timeslot. The guard-time between bursts and the segmentation-less feature has a considerable impact on the network performance.

EPONs are composed by two types of active terminals: the OLT and the ONU. The signal is split by a passive optical splitter at the far end of the network. It is also possible to cascade

the splitters, but it would lead to additional power losses. In such cases, it is important to consider that the optical power budget (power loss across the network path) should not be overtaken. In general, it can be said that the more passive devices taken in the network trunk, the less split ratio and/or the less distance covered.

2.1.1 The MAC layer

The MAC Control Layer is divided in two sublayers: the MPCP (Multi-Point MAC Control) and the Reconciliation sublayer as depicted in Figure 2.

The MPCP is devoted to control the access to the upstream channel amongst the subscribers, perform a discovery process, and allocate bandwidth to each ONU. MPCP is a request-permit protocol. Two main control messages are defined:

- GATE: sent by the OLT to the particular ONU, indicating the time and the bandwidth allocated to it
- REPORT: sent by the ONU to the OLT, indicating the queues occupation in order to request bandwidth for the next cycle

In each cycle, every ONU is polled, so that a REPORT message must be sent to the OLT even if its queues are empty and no bandwidth is requested. Moreover, the OLT periodically sends control messages to discover new ONUs aiming to join the network – the so-called 'autodiscovery' mode.

The algorithm to allocate the bandwidth to each ONU is an important issue to consider. However, attention must be paid to the fact that such algorithm is not defined by the standard – it is instead left open to the implementer. Section 5 is devoted to a brief survey on such algorithms, i.e. the scheduling framework and the allocation computation itself. The efficiency of such mechanism impacts directly the QoS perceived by the user.

2.2 The GPON standard. Gigabit in the access network

GPON was developed by the Full Service Access Network (FSAN) group. It is somehow based on the former ATM access networks (APON, BPON), but GPON's data encapsulation (GEM) is more generic, and accepts different network protocols, such as ATM, Ethernet and IP.

The GPON is a point-to-multipoint network as well, with two types of active terminals: the OLT and the ONT/ONU. The user's equipment is called ONT or ONU if no users are directly connected to the device. Finally, the network path itself is known as ODN (Optical Device Network) and it is usually integrated by fiber and a passive optical splitter.

2.2.1 The MAC layer

The basic transmission unit is called T-CONT (Transmission Container). The bandwidth is guaranteed by allocating timeslots to the ONU in order to transport the T-CONT of each communication. The bandwidth allocation algorithm is also of the request-permit type and it is performed at the OLT. The ONU requests bandwidth each cycle, and the OLT allocates the guaranteed transmission window in the cycle to each active ONU. Two operations modes are possible:

- SR (Status Reporting)-DBA, where the ONU requests bandwidth to the OLT;
- and NSR (Non Status Reporting)-DBA, where the OLT monitors the incoming traffic flows but no information is sent to the OLT from the ONUs.

2.2.2 Service provisioning

The GPON standard specifies the services supported more accurately. They match very closely those defined in ATM networks:

- Asymmetric: Digital broadcast services, VOD, file download, etc.
- Symmetric: e-mail, file exchange, distance learning, telemedicine, etc.
- Synchronous: POTS, ISDN and circuit emulation (E1, T1). Such service is typically of the narrow band but more strict and time bounded.

2.3 Comparison amongst both standards

A summary of both standards is shown in Table 1. There is a common concern that the ATM-oriented technology – BPON, GPON – performs very well when the traffic is of the real time and emulation service, i.e. T1/E1 type; while Ethernet-oriented networks perform better when the traffic is mostly composed by pure data applications, i.e. Internet. Nonetheless, it is not so simple to make a definitive statement about the performance, mainly because the data collected depends on many parameters, and more importantly, on the implementation. Reference (Hajduczenia et al., 2007) concludes that in comparable system set-ups, GPON performs slightly better than EPON, but it is not yet a definitive statement.

Item		ITU G.984	IEEE 802.3 ah
MAC Layer	**Service**	Full services (Ethernet, TDM, POTS)	Ethernet data
	Frame	GEM frame	Ethernet frame
PHY Layer	**Distance**	10 / 20 km (logical: 60 km)	10 / 20 km
	Split ratio	64 (logical: 128)	64 max.
	Upstream (bit rate)	155 Mb/s, 622 Mb/s, 1.25 Gb/s	1.25 Gb/s
	Downstream (bit rate)	1.25 Gb/s, 2.5 Gb/s	1.25 Gb/s
	Bandwidth	Same as above (NRZ coding)	1Gbit/s (8B10B coding)
	Opt. Loss	15 / 20 / 25 dB	15 / 20 dB
	Wave-length	Down : 1480-1500 nm Up : 1260-1360 nm	Down : 1480-1500 nm Up : 1260-1360 nm
	Efficiency	95%	89%

Table 1. Comparison between legacy GPON and EPON

From the table above, it is important to remark that the power budget limits drastically the range of the network and the split ratio, which is typically 64 or less in both standards.

2.4 Summary

EPON is a natural extension of the LAN systems – it bridges the gap between the LAN and Ethernet based MAN/WAN structures. GPON, on the other hand, uses a novel

encapsulation mechanism, GEM. It is important to emphasize that the GPON has the ability to fragment and reassemble frame fragments, including Ethernet frames. The upstream format shown by both standards is depicted in Figure 3(a) and (b).

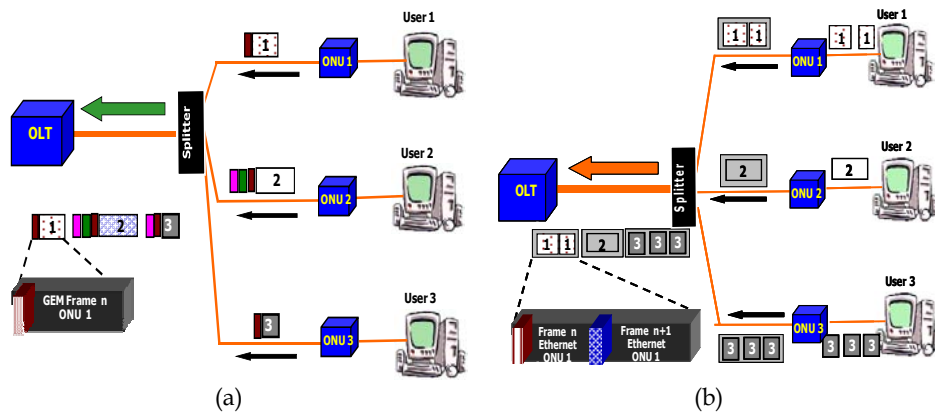(a)   (b)

Fig. 3 Upstream channel transmission (a) GPON. (b) EPON

Optical devices determine the resulting system price. EPON hardware parameters are very relaxed, and therefore are more cost effective. On the other hand, GPON systems, due to their more strict hardware requirements, are more expensive.

Moreover, EPON networks are widely deployed in the APAC regions – by the end of March 2007 there were approximately 8 million subscriber ports and 16 million CO port capacity deployed, while GPON networks was mainly on the trial phase (Hajduczenia et al., 2007). In contrast, other reports predict that GPON will overtake EPON as the pre-dominant technology in a short or mid term. Some equipment manufacturers have announced the introduction of a new family of GPON integrated access device (IAD) semiconductors that are expected to offer high levels of integrations and better throughput performance.

The growth rate of PON deployments are of the order of 3 to 4 million subscriber ports every 6 months, mainly in the APAC countries (Japan, Korea, China, etc.); GPON is expected to grow first in Europe.

3. Next Generation Access networks (NGA)

Technological advances, especially in optical transmission devices, boost the upgrading of current TDM-PON to the NGA. Benefits expected are (Heron et al., 2009):

- High Capacity, up to several gigabits per seconds
- Increased reach, allowing to include more homes and/or to reduce the number of COs
- Wireless and wireline integration, with wireless nodes deployed deeper in the network
- Operation improvement, broadband services or evolved existent services
- Moreover, NGA are more cost-effective than the current ones, specially because CAPEX and OPEX are significantly reduced.

The 10G-EPON standard (IEEE 802.3av) was approved on September 2009, whereas the schedule for the 10G GPON is to be approved in 2010.

3.1 Next Generation 10G EPON. IEEE 802.3av

The next-generation TDM-EPON is upgraded up to 10 Gb/s by the IEEE 802.3av standard. The standard pursues the objectives listed below:

- To support subscriber access networks using point-to-multipoint topologies.
- To standardise two different single mode (SM) fiber data rate channels: symmetric - 10 Gb/s both down and up; and asymmetric - 10 Gb/s in the downstream channel and 1 Gb/s in the upstream channel.
- To have a BER better than 10^{-12} at the PHY service interface.
- To define up to 3 optical power budgets that support split ratios of 1:16 and 1:32, and distances of at least 20 km.
- To maintain a complete backward compatibility with legacy standards.

The goal is to upgrade the channel capacity for both upstream and downstream channels gracefully, while maintaining the logical layer intact, taking advantage of the already existing MPCP and DBA agent specifications. Moreover, 10G-EPON keeps on utilizing the analog video delivery systems before such delivery shifts gradually to an IP-based distribution system.

3.1.1 The 10G EPON. Physical layer

In this section, the main enhancements of the PHY layer are briefly explained. Table 2 illustrates the acronyms used to designate the new EPON power budgets:

Power Budget class	Power insertion loss	Downstream	Upstream	Split -ratio	Range (Km)
PR10	20 dB (low)	10 Gb/s	10 Gb/s	1:16	10
PR20	24 dB (medium)	10 Gb/s	10 Gb/s	1:16 (1) 1:32 (2)	20 (1) 10 (2)
PR30	29 dB (high)	10 Gb/s	10 Gb/s	1:32	20
PRX 10	20 dB (low)	10 Gb/s	1 Gb/s	1:16	10
PRX20	24 dB (medium)	10 Gb/s	1 Gb/s	1:16 (1) 1:32 (2)	20 (1) 10 (2)
PRX30	29 dB (high)	10 Gb/s	1 Gb/s	1:32	20

Table 2. 10G EPON acronyms and Power Budget classes

Notice that the physical-medium-dependent (PMD) and Power-Budget-Class (PBC) naming nomenclature for 10 Gb/s EPONs, is different than those for legacy EPON. Table 3 illustrates the differences between legacy TDM- EPON and 10G EPON in detail.

3.1.2 Wavelength allocation

The downstream 1 Gb/s and 10 Gb/s data streams will be WDM overlaid thus creating indeed two independent P2MP domains.

- The 1 Gb/s downstream link remains centered at 1490 ± 10 nm
- The 10 Gb/s downstream link uses 1575-1580 nm wavelength band.

	1G EPON	10G EPON
channel coding	8B10B	64B66B
Data rate (DS / US)	1 Gb/s 1 Gb/s symmetric	- 10 Gb/s 10 Gb/s symmetric - 10 Gb/s 1 Gb/s asymmetric
Upstream (λ)	1260 – 1360 nm	1260 – 1280 nm
Downstream (λ)	1480 – 1500	1575 – 1580
# of PBC	2	3
Split ratio	1:16	1:16 / 1:32
FEC	RSS (255,239) (optional)	RS (255,223) (mandatory)

Table 3. Differences between 1G and 10G EPON

For the symmetric line-rate scenario, WDM channel multiplexing in the upstream channel is discouraged due to increased cost for the ONU. The 10-Gb/s upstream channel will use the optical window centered at 1310 nm, which is the currently the allocated window for 1 Gb/s upstream channel.

The OLT should operate in a dual rate mode; therefore, an overlay dual stack structure will need to be implemented from the PMD up to the Reconciliation sublayer. An OLT supporting both downstream channels may multiplex the outputs of two transmitters using DWDM coupler, while the optical filters at an ONU are tuned to receive one downstream wavelength.

3.1.3 The 10G EPON MAC layer. The MPCP protocol
The MPCP protocol is essentially the same in both 1G and 10G EPON networks. It should also be considered that, for the coexistence of various line rates, the DBA in the OLT will be responsible for scheduling not one but two mutually cross-dependent EPON systems, sharing a single upstream channel but expecting only minor changes to the MPCP protocol. As in legacy TDM–PONs, the DBA is out of the scope of the IEEE802.3av standard, and thus left vendor-dependent.

3.2 Next Generation 10G GPON (NG-GPON)
The FSAN Group has been very active in upgrading the legacy GPON. The basic requirement of NG-GPON is to offer higher capacities than GPON while maximizing the re-use of protocols, components and infrastructure. It is mandatory to maintain the compatibility and the coexistence with the legacy GPON systems already deployed. Such upgrade will focus mainly on the physical layer - upgrading the rate to 10 Gb/s - but also on the optimization of Ethernet service delivery.

3.2.1 Wavelength allocation
To reach such goal the ITU community first developed the standard G.984.5 (ITU-T G.984.5, 2007) to reserve wavelengths for the next-generation applications. Summarizing, the G.984.5 entails:

- Wavelength ranges to be reserved for future use. Service signals are overlaid via WDM on an operating GPON system. Three optional enhancement bands (options 1, 2 and 3) are specified as depicted in Figure 4.
- Blocking filters to be supported at GPON ONT/ONU to ensure that next-generation ONUs could be installed on currently deployed GPON, side by side with legacy GPON ONT/ONU.
- GPON upstream wavelength reduction options, to free spectrum in the O band for future services.
- And of course, allowing operators to gradually migrate from a working GPON ONT/ONU to a NG-GPON ONT/ONU without disrupting existing customers.
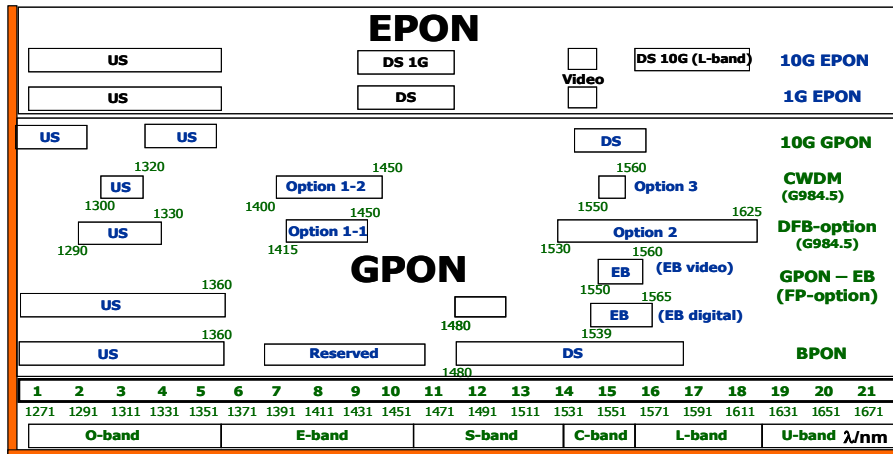

Fig. 4. Joint wavelength allocation proposals of 10G EPON and 10G GPON

3.2.2 10G GPON evolution

Two evolution stages will compose GPON evolution: in the first step, NG-GPON1 (expected in year 2010) will be fully compatible with legacy GPON. Its two expected goals are:

- A GPON supporting 10 Gb/s downstream, and 2.5 Gb/s upstream (referred to as XGPON1).
- A GPON supporting symmetric service, 10 Gb/s downstream, and 10 Gb/s upstream (referred to as XGPON2).
- A WDM option to overlay multiple GPONs and/or point-to-point overlays with different wavelengths (i.e. WDM) on the same fiber infrastructure.

NG-GPON1 stage will be compliant with G984.5, therefore GPON legacy ONTs/ONUs could be replaced one by one by new 10G GPON ONTs/ONUs or even added to an existent ODN.

Some voices propose a WDM-PON as an alternative solution to avoid the technical hurdles of the NG-GPON. Among others, WDM-PON has clear advantages because it combines the traditional PON low infrastructure cost, with the use of "colorless" optics, thus reducing management complexity.

Finally, the second step called NG-GPON2 is expected to come later (by 2015). It aims to develop a new GPON (probably disruptive) that does not require coexistence with Legacy service. Other tehnologies may be considered, like higher line rate, DWDM, OFDM, and others (Kani et al., 2009).

3.3. 10G EPON/GPON convergence

Finally, the xPON industry supports the development of a framework that will allow 10G PON standard networks to converge. Such goal is extremely interesting in order to reduce costs, thus increasing the 10G PON deployment worldwide.

The convergence may be achieved in two ways:

- Firstly, by aligning the 10G optics of an ITU NG-PON system with the optical layer specification of the emerging IEEE 10G EPON. In fact, optical layer specifications now being used by IEEE are more aligned with ITU optical budget rules than ever.
- Secondly, it will be also possible to develop an open extensible interface to the MAC control channel – for instance, an enhanced interface might be added to the 802.3av systems that allows the convergence with the ITU standards.

4. New Trends: the WDM-PON and Long-reach PON

The new Internet media services, such as symmetrical HD real time applications, videoconferencing, and broadcast, among others, followed by the new type of communications, like point-to-point or multipoint-to-point, increase drastically the end-user bandwidth demand. This bandwidth has an exponential growth that should cope with deployments of next generation optical access networks. The evolution of legacy PON technologies (GPON/EPON) should provide huge network resources and cost-effective solutions to fulfill the new user applications and network provider demands.

Requirements of Long-Reach NGA are listed below:

- Extend the geographical reach to a minimum of 100 Km
- Increase the split ratio up to 128 or more, reducing the cost per subscriber
- Increase the downlink and uplink throughput (evolution to 10 Gb/s)
- Be transparent or compatible as much as possible with current legacy PONs
- Reduce the CAPEX and OPEX (operation, deployment, and maintenance).

Finally, it is also desirable for NGAs to be deployed in a reasonable temporal horizon, 2010 to 2015, using available technologies (lasers, APD, amplifiers, new modulation schemes).

Several proposals are being launched by the standardization bodies (mainly ITU and IEEE), as well as research projects and position research papers; however, few approaches cover the previous requirements in their totality. The Long Reach Optical Access Network (LROAN) objective is to increase the reach of Optical Access Network under a common umbrella. It was proposed as an extension of the PLANET ACTS project, developed in the late 90s with a split ratio of 2048 users over 100 Km at 2.5 Gb/s downstream rate, and 311 Mb/s upstream rate (Van de Voorde et al., 2000).

4.1 LR-PON based on the legacy GPON

The recent standard G984.6 (ITU-T G.984.6, 2008) defines a new enhancement of the legacy GPON by extending the optical budget, and thus allowing the deployment of a longer reach and a higher split ratio. The increase of the reach in GPON is achieved using mid-span optical amplifier extenders, transponders or single side extenders.

The amendment allows a mid-span reach extension by adding an active device to the passive ODN (Regenerator or Optical Amplifier) in the fiber link, between the OLT and ONT, achieving a longer range of up to 60 km [see Figure 5].
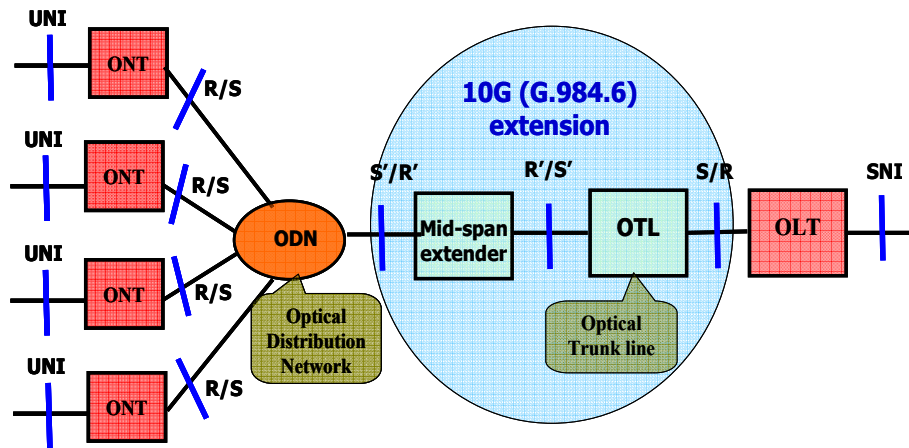

Fig. 5. GPON extension architecture (ITU-T G.984.6, 2008)

The remote OLT is connected with the mid-span extender through an Optical Trunk Line (OTL). In the same way, the ONUs are connected to mid-span using an optical distribution network (ODN) through the R/S and S'/R' interfaces. Reach extended (GPON-RE) adds a long point-to-point trunk line (OTL) to a point-to-multipoint GPON ODN. GPON-RE avoids metro network equipment, installing the OLT in the remote central office. Such proposal reduces the number of central offices, and at the same time it applies the same split independently of their topology and geography, simplifying the OAM operation.

Other approaches should maintain compatibility with existing OLTs to the maximum possible extent. The extension of the reach of the PON or alternatively the split ratio of the PON is penalized by adding an active device, thus converting the existent PON into an active PON.

The reach extender must be compatible with existing GPON 2.4/1.2 Gb/s rated ONT equipment and ODN (power budget class B+). In the past, however, the extender supporting a more capable ODN had already been defined as class C+ in the amendment G.984.2.

The mid-span can be built with SOA amplifiers operating in the O band (1310 nm) and the S band (1490nm). New devices such as wavelength filters and optical filters will be used to extend the reach of the OTL up to 50 km and to increase the loss budget up to 54 dB. Optical amplifiers, however, are expensive and not transparent – therefore, a 3R regenerator is needed. A 3R-RE is composed by OLT and ONT transceivers: it re-amplifies, re-shapes and re-times the signal. Nevertheless, such solution is not compatible with the legacy GPON.

4.2 Long Reach WDM PON

WDM-PON is the application of wavelength-division multiplexing that uses individual wavelength for each PON network. ONUs have light sources at different tuned wavelengths coexisting in the same fiber, increasing the total network bandwidth and the number of users served in the optical access network. Related to communications mode, the WDM-PON may use point-to-point communications, point-to-multipoint (like EPON/GPON trees by each wavelength), or hybrid solutions. In the point-to-point, no dynamic bandwidth allocation mechanisms are needed. The point-to-multipoint uses a WDM/TDM, achieving high resource utilization efficiency.

At the same time, the ONU/ONT in a WDM-PONs are classified as: colorless or colored. In the former one, the optical user terminal is wavelength-seeded from the remote OLT located in the central office, using the same wavelength path for downstream and upstream channels. In this case, the upstream optical flow is modulated using FSK, inverse return-to-zero (RZ), or intensity modulation (IM) (Shea & Mitchell, 2009), (Martinez et al., 2008). Such device is the preferred one because network management is gracefully reduced.

The splitter is replaced by a wavelength selective filter implemented with an arrayed waveguide grating (AWG) when the ONU is color-sensitive and the communication mode is of the point-to-multipoint type.

Long reach WDM-PON is feasible using low-loss AWG – in this case, the link budget is 28 dB, the splitting ratio is up to 64, and the reach increases to up to 80 km. The reference (Mukherjee, 2006) explains largely the current WDM technology.

4.3 Long Reach DWDM-CDM PON

DWDM-CDM PON combines the code and wavelength-division multiplexing, achieving ultra-long range due to coding gain, high bandwidth and bidirectional transmission on the same wavelength and with a single fiber.

Typical figures are 16 λ DWDM-CDM PON, with a power budget of 42 dB at 100 km, with 32 orthogonal codes (32 users).

Some of this long reach schemes provide high split ratio, long reach -greater than 60 km-and high symmetrical and asymmetrical bandwidth (10/2.5 Gbps) (Iwamura et al., 2007).

4.4 Current research in WDM / Long-reach networks: a survey

A proposal for a long-range architecture was implemented by the ACTS (Advanced Communications and Technologies and Services) project, called Photonic Local Access NETwork (PLANET) (Van de Voorde et al., 2000). The splitting factor was 2048 with a span of 100 km in the PLANET project. The span comprehends a maximum feeder length of 90 km and a drop section of 10 km. The transport system supported on this SuperPON architecture was based on an asynchronous transfer mode (ATM) cell. A bit rate of 2.5 Gb/s was distributed to the optical network units (ONU) by time-division multiplexing (TDM) in the downstream direction, whereas a time-division multiple access (TDMA) protocol was used to share the 311 Mb/s upstream bit rate. In order to compensate the fiber and splitting ratio losses, some optical amplifiers were housed in optical repeater units (ORUs) located at the feeder section and between the feeder and the drop sections.

Another related proposal on LR-PON is the SuperPON architecture based on GPON by British Telecom. This is a GPON over 135 km consistent with the standards of ITU-T. The

channels are 2488 Gb/s downstream and 1244 Gb/s upstream, using ~1490 nm and 1552,924 nm wavelengths. Advanced 40-λ dense-wavelength-division-multiplexing (DWDM) equipment is used to extend the physical reach and to provide fiber gain. Each wavelength can support a split of 64 (1 × 8 followed by 1 × 8), so that a fully populated system could support 2560 ONUs. The combined loss of the splitters and the last 10 km of the fiber is 23 dB. The Hybrid DWDM-PON (Shea & Mitchell, 2009) by University College presents the extension in the reach toward 100 km and an upstream bit rate of 10 Gb/s. It can potentially support 17 TDM PONs operating at different wavelengths – each with up to 256 customers, giving an aggregate number of 4352 customers in total. It uses 100-GHz channel spacing, and divides the C-band into two, with one half (1529–1541 nm) carrying downstream channels and the other (1547.2–1560.1 nm) carrying upstream channels.

Further implementations using DWDM in the backhaul to increase the fiber efficiency are demonstrated in the EU project PIEMAN (Shea & Mitchell, 2007). In this architecture, the network has a 100-km reach with a 32 wavelength DWDM backhaul. Each 10 Gb/s wavelength is uniquely allocated to a PON with a 512-way split, enabling the network to support (32 × 512) up to 16,384 users with an average bandwidth of ~20 Mb/s. By using dynamic bandwidth allocation and 10 Gb/s-components in the ONU, it is possible for each user to burst at 10 Gb/s. [see table 4]

Project	Reach (Km)	# λ	DS/UP (Gb/s)	# ONTs
PLANET	100	1	2.5/0.311	2.048
Super-PON	135	40	2.5/1.25	2.560
Hybrid PON	100	17	10/10	17*256=4.352
PIEMAN	100	32	10/10	32*512=16.384
SUCCESS	25	4*16	1.25/1.25	4*16
SARDANA	100	>1	10/10	1000

Table 4. Long Reach-PON projects

One of the most promising recent WDM-PON network, is the so-called SUCCESS network (Kazovsky et al., 2007). The SUCCESS-HPON architecture is based on a topology consisting of a collector ring and several distribution stars connecting a central office (CO) and several optical networking units (ONUs). It uses Coarse WDM (CWDM) and dense WDM (DWDM) technologies. Each ONU has its own dedicated wavelength for both upstream and downstream transmissions on a DWDM grid to communicate with the OLT. The communication is a half-duplex communication – the tunable transmitters at the OLT are used for both downstream and upstream modulated frames by ONU's. Furthermore, a scheduling algorithm has been developed to keep track of the status of all shared resources and arrange them properly in both time and wavelength domains, including the control for both tunable transmitters and tunable receivers. The research is also focused on the evaluation performance of two scheduling algorithms: 1) batching earliest departure first (BEDF); and 2) sequential scheduling with schedule time framing (S3F).

Lastly, there are also important investments in optical technologies in Europe. The current FP7 framework of the CE launched in 2007 funds several projects related to optical technologies. Amongst others, is interesting to consider the project called Single-fiber Advanced Ring Dense Access Network Architecture (SARDANA) – its goals are quite ambitious: up to 1024 users per PON, 10 Gb/s data rate, remote passive amplification and

wavelength-agnostic customer equipment. Finally, it also aims to score well in traffic balancing, as well as being highly scalable and allowing cascading (Prat, 2008).

5. Dynamic Bandwidth Allocation (DBA) and QoS provisioning in EPON

One of the main challenges of a TDM-PON is to schedule the transmissions and the bandwidth allocation in the upstream shared channel efficiently. The issue of developing appropriate scheduling algorithms was an important topic of research in the past. Goals of the scheduler are: be efficient; support the QoS of each traffic flow requirements; allocate fair bandwidth to users reducing delay and jitter; and finally, it must be computationally simple enough.

To guarantee the efficiency and scalability of EPON in terms of resource management, numerous contributions have been presented. There are two main strategies: the fixed bandwidth allocation (FBA), and the dynamic bandwidth allocation (DBA). The first one allocates the same transmission slots to every ONU in every service cycle. It is a simple scheme but it does not perform optimally. On the contrary, the dynamic policy allocates the transmission in the upstream channel based on each ONU's requested bandwidth, consequently the dynamic scheme provides a more fair, efficient and flexible bandwidth allocation.

5.1 DBA algorithms legacy EPON network
The DBA of the EPON should acomplish QoS requirements to deliver different services, such as multimedia traffic. DBA algorithms proposed so far for EPONs deal with different criteria and can be categorized as shown in Figure 6.
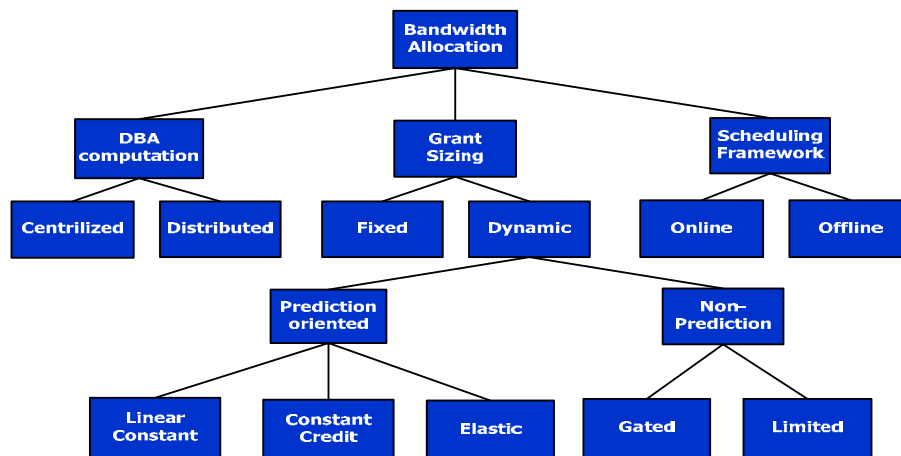

Fig. 6. Bandwidth Allocation Criteria

DBA algorithms may be either centralized or distributed. Besides, the dynamic grant sizing –bandwidth allocation- might be based on a prediction oriented or non-prediction oriented approaches.

Some examples of algorithms prediction-oriented are: (Hee-Jung Byun et al., 2003), (Yuanqiu Luo & Ansari, 2005), (Yongqing Zhu et al., 2006) and (Lannoo et al., 2007). Finally, authors in reference (Kramer et al., 2002b) proposed different DBAs explained in the IPACT section below.

On the other hand, the scheduling framework determines the way scheduling decisions are made. There are two main frameworks to consider: online and offline scheduling. With online scheduling, the OLT makes scheduling decisions "on-the-fly" based on individual requests and without global knowledge of the network. On the other hand, offline scheduling requires a full knowledge of the network status, thus its scheduling decisions are computed after having received the requests from all of the ONUs. (McGarry et al., 2006).

In many settings, the online scheme performs better than the offline scheduling, but with less control of channel transmission times.

5.2 Centralised vs. distributed scheduling

The OLT computes the bandwidth allocation in the centralised scheduling, which is the most common approach. On the other hand, the distributed approach contemplates the participation of both OLT and ONUs. Bandwidth allocation is calculated by ONU though it is also authorized by OLT.

In what follows, we present a description of a centralized DBA, the Interleaved Polling with Adaptive Cycle Time (IPACT), and a distributed DBA, Dynamic Distributed Scheduler for EPON (DDSPON), and a performance comparison among them.

5.2.1 IPACT

The IPACT is one of the early works that became very popular in the literature (Kramer et al., 2002b). The cycle period adjusts to the bandwidth requirements of the ONUs, and the definition of a maximum transmission window does not allow ONUs with high traffic level to monopolize the bandwidth resource.
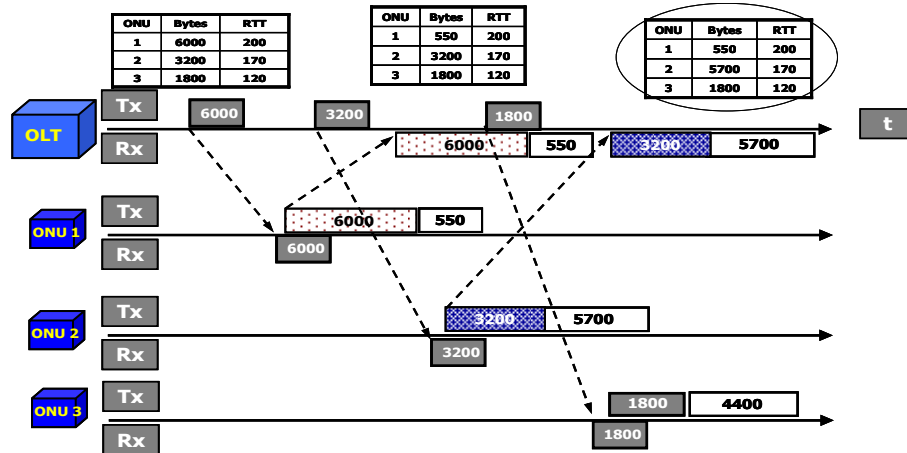

Fig. 7. Interleaving Polling mechanism in IPACT (Kramer et al., 2002b).

What is more interesting in this proposal is that IPACT uses an interleaved polling approach, in which the next ONU is polled before the transmission of the previous one is finished in order to utilize the efficiently the channel, as depicted in Figure 7.

The IPACT grant sizing is performed using five different alternatives: fixed, limited, gated, constant credit, linear credit and elastic. Summarizing, the prediction-oriented DBAs are: constant credit, linear credit and elastic. The credit approach - constant or linear - grants the ONU's requested bandwidth plus an extra amount of bandwidth; while the elastic approach basically limits the maximum cycle time. The rest of the options – fixed, limited and gated- are non prediction-oriented DBAs. The limited approach allocates no more than a predefined amount of bandwidth to an ONU; and the gated one grants the requested bandwidth without any limitation. Finally, the authors demonstrate that the limited discipline is more efficient than the gated one and it has been the most preferred one to compare with in the literature.

5.2.2. DDSPON

The DDSPON (De Andrade et al., 2007) is a DBA developed by some of the authors of this chapter. This DBA requires an MPCP extension, because some extra information must be supplied and therefore carried in control messages – mainly the weight vector (Φ). This data vector allows ONUs to compute its transmission window size. Such parameter represents a proportional weight set up according to each ONU's guaranteed bandwidth agreement. The ONU computes the required bandwidth (R_i) and its current weight Φ_i , and then reports such value to the OLT in a report message. The interleaving polling mechanism is applied here as well as IPACT does [see Figure 8].
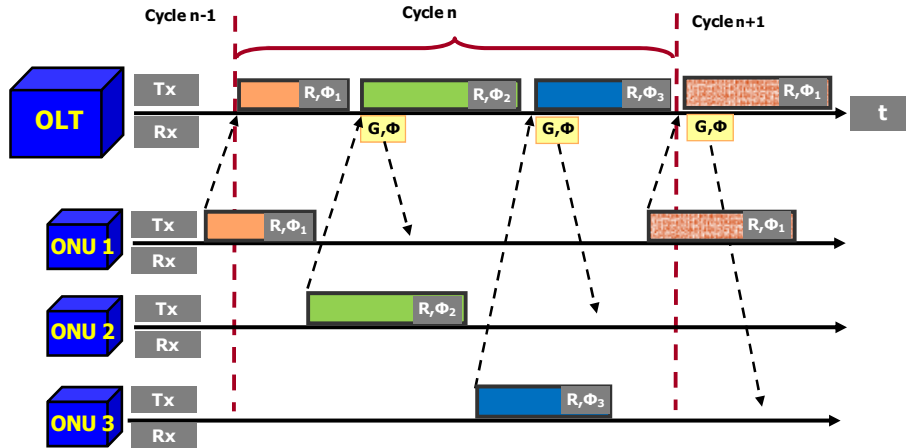

Fig. 8. DDSPON Polling Mechanism.

The average transmission window size of ONU$_i$ is computed by the equation below:

$$W_i = \frac{\Phi_i}{\sum_{j=1}^{N} \Phi_j} W_{MAX} \; ; \; \left[\mathrm{N} \; : \; \text{of} \; \mathrm{ONUs} \; \right] \tag{1}$$

where W_{MAX} is the maximum transmission window size (bits) that corresponds to the maximum cycle time (T_{MAX}).

$$W_{MAX} = T_{MAX} * Upstream\ rate \qquad (2)$$

The DDSPON process is as follows:

- The OLT receives a report messages from ONU_i along the cycle n containing the window size ($R_i(n)$) computed by itself as in equation 5, and the weight (Φ_i)

ONU_1	ONU_2	ONU_3	......	ONU_N
$\Phi_1(n)$	$\Phi_2(n)$	$\Phi_3(n)$	......	$\Phi_N(n)$

- The OLT sends the Gate message to the ONU in the next cycle (n+1) including the weight vector Φ (with weights of all other ONUs) and the time to start the ONU's transmission. Then, the ONU_i transmits the data according to the value of $R_i(n)$ previously computed, and calculates the new values of $R_i(n+1)$ and $\Phi_i(n+1)$.

$$W_i(n+1) = \frac{\Phi_i^{conf}}{\Phi_i^{conf} + \sum_{j=1;j\neq i}^{N} \Phi_j(n)} W_{MAX} \qquad (3)$$

And $R_i(n+1)$ is computed

$$R_i(n+1) = \min\left(W_i(n+1), Q_i\right); \left[Q_i : queue\ size\right] \qquad (4)$$

Finally, the new weight for next cycle n+1 is calculated based on the request value for cycle n+1:

$$\Phi_i(n+1) = \frac{R_i(n+1)\left[\Phi_i^{conf} + \sum_{j=1;j\neq i}^{N} \Phi_j(n)\right]}{W_{MAX}} \qquad (5)$$

Notice that each ONU schedules the size of its transmission window dynamically. DDSPON is executed in an online framework because the scheduling process is executed without the need of waiting the reports from the rest of the ONUs. Moreover, by getting the weight vector, each ONU is able to get an 'idea' of the rest of the ONUs' loads, which is characteristic in offline DBAs.

5.2.3. Performance evaluation
This section illustrates the performance evaluation of DBA algorithms. First we define the power ratio as in equation (Kleinrock, 1975):

$$P = \frac{\phi_{max}}{D}; \quad \begin{array}{l} \phi_{max} : \text{throughput} \\ D : \text{delay} \end{array} \qquad (6)$$

The power ratio evaluates the DBA's efficiency. Therefore the performance is evaluated by computing: packet delay, average queue size and throughput for different setting scenarios from low to high offered loads.

The comparison between DDSPON versus the IPACT was conducted by event-driven simulations using the OPNET Modeler simulator. These simulations considered an ideal channel and identical network parameters. To be more accurate, the distance parameter was modified through the different scenarios of simulations from long (20 km) to short distances (5 km), and the traffic model considered was self-similar in order to obtain more realistic results.

The setting scenario consists of 16 ONUs with the same nominal weight (1/16), 1 Gb/s line rate, 8 μseg. guard interval, large buffer size to avoid packet drops, and finally single traffic class per ONU.

The main results obtained are presented below. Firstly, Table 5 below presents the average queue size and packet delay for different offered loads and in the long distance scenario.

Offered load	Average queue size (bytes)		Average packet delay (ms)	
	IPACT scenario 1	DDSPON scenario 1	IPACT scenario 1	DDSPON scenario 1
0,05	942	694	0,286	0,29025
0,2	1809	1890	0,373	0,41108
0,4	3292	3497	0,567	0,62216
0,6	7078	6766	1,050	1,00087
0,8	157538	59307	19,095	7,09164
1	425367	148205	41,337	14,3108

Table 5. Queue and delay size (average) for 20 Km

Figure 9a presents the average packet delay, and Figure 9b presents the average queue size for different distances in a high loaded scenario (H=0.8). Notice that results provided have important implications, for instance the IPACT requires larger buffer size to avoid the packets loss than DDSPON.
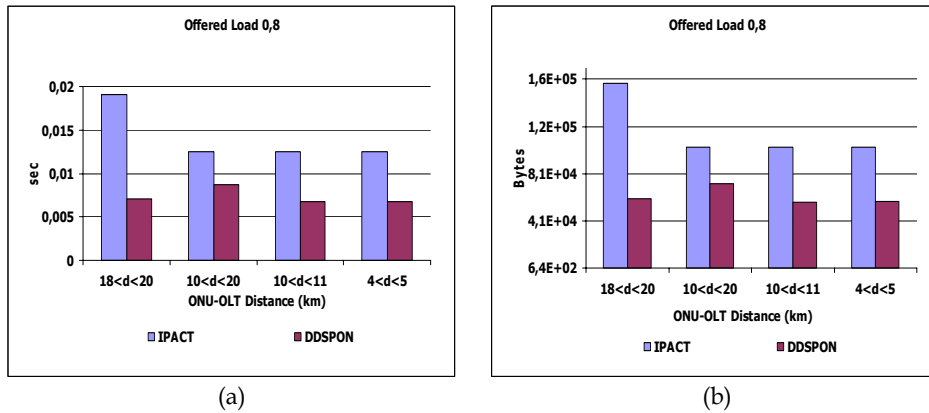

(a)   (b)

Fig. 9.Average comparison between IPACT and DDSPON. (a) packet delay (b) queue size.

It is interesting to consider in the figures above that DDSPON presents an increase in both, the average queue size and average packet delay, when the setting scenario is heterogeneous, i.e. ONUs are far distributed between 10 and 20 km, this variation is roughly about 21% higher (for loads of 0,8) than the results obtained in the homogeneous scenario. Figure 10 clearly shows that IPACT's average packet delay is worse than the DDSPON's one. The percentage of improvement of DDSPON over IPACT goes from 30.6% to 65.4% for the different distance ranges.
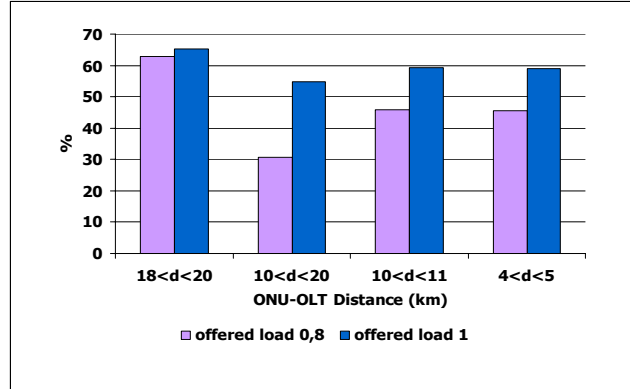

Fig. 10. Average packet delay percentage difference: DDSPON over IPACT.

To conclude, the DDSPON remains stable versus IPACT with the variation of distances, and the most remarkable is that DDSPON presents significant improvements versus the IPACT in all simulations performed, being more relevant in highly loaded scenarios.

5.3 QoS provisioning in an EPON

The bandwidth allocated to each ONU is guaranteed by the DBA (inter-ONU scheduling), but the QoS is guaranteed internally by the ONU, the so-called intra-ONU scheduling process. The EPON follows the IEEE QoS policy defined in the standards IEEE 802.1P/Q. There are up to eight sub-queues in each ONU depending on the traffic type; the intra-ONU scheduling is of the strict type, hence, queues are served in order of priority. Such procedure does not perform optimally in light load networks, so many algorithms, such as (Hsueh et al., 2003), (Kramer et al., 2002a), (Jing Xie et al., 2004), (Kramer et al., 2004) or (Yuanqiu Luo & Ansari, 2005) among others, propose to maximise intra-ONU scheduling.

According to the QoS policy, (McGarry et al., 2004) classifies DBA algorithms into two categories: algorithms with statistical multiplexing (no QoS guaranteed), and algorithms with quality of service. The latter is further separated into algorithms with absolute QoS assurances, i.e. those that follow the integrated services paradigm; and algorithms with relative QoS assurances, which provide different QoS levels according to the traffic classes, i.e. differentiated services.

DBA algorithms introducing the support of differentiated services use strict priority scheduling. Some of the examples developed in the past can be listed: (i) in (Choi & Huh, 2002), where bandwidth is allocated according to traffic priority requests; (ii) in (Kramer et al., 2002a), which combines IPACT and strict priority queuing in order to support QoS; (iii)

(Assi et al., 2003) introduced an approach that consists of distributing the fairly excessive bandwidth amongst the highly loaded ONUs. It takes also into consideration different traffic classes, so that requested bandwidth consists of high, medium and low priority; and (iv)in (Jing Xie et al., 2004), the authors propose the division of the frame, but in this case the frame is divided into multiple subframes according to the different traffic classes, in order to reduce the delay of high priority and medium priority classes; the size is variable depending on the request, and through the definition of weights for each class, it is possible to avoid bandwidth monopolization.

The aforementioned algorithms are the main contributions regarding DBA with differentiated QoS support; more references can be found in (Zheng & Mouftah, 2009). Furthermore, QoS contributions in DBAs are summarized in (McGarry et al., 2008).

5.4 Enhanced DBA algorithm for WDM-EPON networks

To provide higher bandwidth in PONs, a WDM technique can be performed incorporating multiple wavelengths in either, the upstream or downstream direction so a WDM-PON has many advantages such as increasing network capacity, in terms of bandwidth or user scalability.

The new challenge for WDM-EPON is to allocate bandwidth to ONUs in both time and wavelength domains, maximizing the whole network efficiency. Therefore, DBA algorithms initially designated for EPON require modifications to exploit the multichannel architecture. The bandwidth management problem can be split into two sub-problems: grant sizing (bandwidth allocation) and grant scheduling (wavelength selection). Such algorithms hereinafter are known as Dynamic-Wavelength and Bandwidth Allocation (DWBA).

Grant sizing is not analyzed anymore because any of the aforementioned DBAs may be used. Instead, two main approaches cope with grant scheduling by: improving a former DBAs, e.g. SIPACT (Clarke et al., 2006); or developing new mechanisms, for instance, applying a well-known scheduling theory (Pinedo, 2002). The backward compatibility of the MPCP is mandatory, but some extensions to the MPCP must be considered to deal with the wavelength discovery and scheduling.

The reference (McGarry et al., 2008) introduces the concept of just-in-time (JIT) which is a hybrid scheduling framework between offline and online. The OLT schedules the grant based on the report messages accumulated since the last channel became available. The ONUs that have not been allocated to a wavelength yet, are scheduled together across all wavelengths as soon as a wavelength becomes available. The online JIT scheduling framework gives the OLT more opportunity to make better scheduling decisions.

The simplest grant scheduling policy is to assign the next available supported channel (NASC) to the ONU which means that the OLT must know which upstream channel will first turn idle according to its polling table; such policy is not optimal in all cases and it does not consider ONUs that support different wavelengths.

The approach of selecting the wavelength by using the scheduling theory seems much better policy (McGarry et al., 2008), e.g. Shortest Path First (SPT), Longest Path First (LPT), and Least Flexible Job First (LFJ) amongst others (Pinedo, 2002). LFJ first schedules transmissions to the ONUs that support the fewest number of wavelength channels at the earliest available supported channel. The LFJ policy is optimal because it minimizes under certain conditions the length of the schedule.
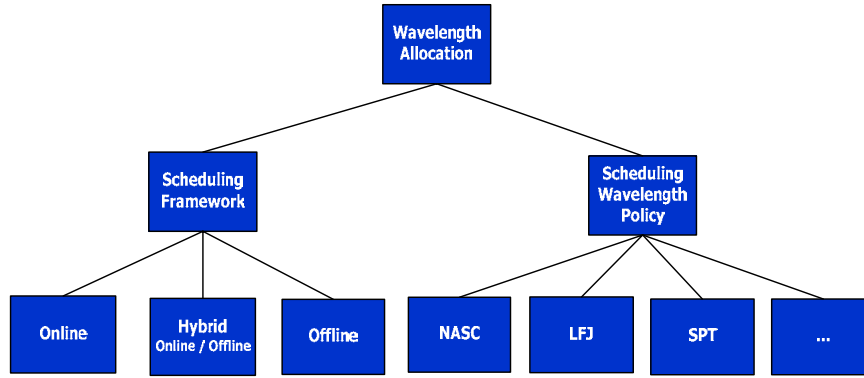
Fig. 11. Wavelength allocation scheduling

Figure 11 classifies the scheduling framework and the scheduling wavelength policies explained above.

5.4.1 Survey of DWBA

As an evolution of IPACT in WDM, some variants of IPACT are addressed in different proposals, e.g. in (Kae Hsiang Kwong et al., 2004). The authors propose an algorithm so-called WDM IPACT with a single polling table (WDM IPACT-ST). The grant scheduling is of the NASC type and the grant sizing is performed according the IPACT (with fixed, limited or gated approach). This approach requires new devices at both ends of the fiber links to support simultaneous transmissions over multiple wavelengths.

In (Clarke et al., 2006), the authors developed a DBA called Simultaneous and Interleaving Polling with Adaptive Cycle Time (SIPACT). SIPACT allows different architectures to poll ONUs, either intra-wavelength (on the same wavelength) or inter-wavelength (amongst different wavelengths), simultaneously but depending on the set of wavelengths supported by each individual ONU.

The authors in (Dhaini et al., 2007) presented several DWBA variants also based on former EPON DBAs algorithms and compared their performance. The three different approaches compared depend on the weight of the individual ONU, the two more interesting ones consider "on the fly" (online) mechanisms. Simulations performed showed that such approach presents a better throughput and delay performance.

Finally, the recent proposal (McGarry et al., 2008) addressed the queuing delay and channel utilization through the scheduling theory, which is concerned to scheduling a set of jobs with specific processing times to be executed on a set of machines. In this case, the ONUs represent the jobs, the grant size is represented by the processing time, and the channels are represented by machines.

6. Conclusions

This chapter discoursed on optical fiber based access networks. While the current backbone networks support high capacities; the last mile for the access network remains a bottleneck. New enhancements of the legacy standards are coming soon allowing the upgrade the

upstream/downstream channel line rate to 10 Gb/s. Such new standards are intended to be compatible with existent Legacy TDM-PONs.

But the more important step towards NGA is the implementation of the WDM technology. There are huge research efforts worldwide in developing metro and access networks based on WDM, using either DWDM or CWDM. The research is focused on improving the optical devices as well as in developing new architectures to handle the multi-wavelength channel efficiently. Such solutions are not only based on the type of network -such as WDM-PON or 10G PON- but also on hybrid technologies such those presented in section 4.

Moreover, incumbent operators are interested in the so-called Long Reach-PON (LR-PON) that will help the growing process of PON deployment. LR-PON is a very cost-effective solution because the CAPEX and the OPEX of the network are lower mainly due to the fact that the number of equipment interfaces, network elements, and nodes are reduced, and moreover, the network management complexity is also simplified.

The allocation of bandwidth to users in the upstream shared channel of the network is addressed by appropriate DBAs. Among them we present IPACT and DDSPON, which are representatives of centralized and distributed DBAs, respectively. The results provided demonstrate that DDSPON is more efficient than IPACT. New DBAs for WDM-PON networks are a key issue to manage and fairly distribute the resources. Proposals presented in section 5, especially those based in the scheduling theory are very promising, but further research should still be carried out.

Furthermore, the new goals are directed to support scalable networks and to help the coexistence between legacy and next-generation PONs.

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