Hybrid WDM–XDM PON Architectures for Future Proof Access Networks

Rodolfo Alvizu, Alfredo Arcia, Maybemar Hernández, Mónica Huerta
Departamento de Electrónica y Circuitos
Universidad Simón Bolívar (USB)
Sartenejas, Venezuela
ralvizu@usb.ve, arcialfredo@hotmail.com, maybemarh@usb.ve, mhuerta@usb.ve

Idelfonso Tafur Monroy
Department of Photonics Engineering
Technical University of Denmark (DTU)
Lyngby, Denmark
idtm@fotonik.dtu.dk

***Abstract*— The design of future proof optical access networks is a challenging and hot research topic. In this work we summarized the requirements for future proof networks and the expected evolution of optical access networks. The current network infrastructure is composed by too many domains where the electronic processing bottleneck must be relieved. The evolution and penetration of Optical Access Networks threatens to create a higher electronic bottleneck at Metro–Access interfaces. In this paper we evaluated an enhanced version of time–wavelength access architecture with optical bypass and traffic self–aggregation based on colorless customer terminals. The purpose of this hybrid Passive Optical Network with Wavelength Division Multiplexing and Time Division Multiplexing architecture is to allow for a transparent Metro–Access interface with low latency and reduced power consumption. The time–wavelength access architecture is based on the nonuniform traffic profile in networks to introduce optical bypass. For comparison a Passive Optical Network with Wavelength Division Multiplexing architecture was used as reference. Simulation results obtained by a developed model in OPNET Modeler showed that the Passive Optical Network with Wavelength Division Multiplexing tends to present electronic bottleneck issues, even though delays and loss rates were not very different in both architectures. These bottleneck issues can be avoided by the introduction of optical bypass and traffic self–aggregation. Optical bypass allows nodes to avoid electronic processing; therefore, delay and power consumption can be reduced. The proposed architecture is an interesting useful approach for Metro–Access integration and future access networks. This paper represents a baseline for future design of hybrid Passive Optical Network with Wavelength Division Multiplexing architectures and optical bypass for traffic self–aggregation. Such hybrid schemes can be based on multiplexing technologies like Orthogonal Frequency Division Multiplexing.**

Keywords– Future access network; optical bypass; Self–Aggregation; Hybrid WDM–PON; Metro–Access.

I. INTRODUCTION

This paper, based on the work showed in [1], presents new results, current trends, and the general scenario for future proof optical access networks. The world has been witnessing an explosion of high bandwidth consuming applications, and an ever rising bandwidth demand by users. According to Cisco's Visual Networking Index, global IP (Internet Protocol) traffic will grow fourfold from 2010 to 2015 [2]. Globally, Internet video traffic is expected to grow from 40% of all consumer Internet traffic in 2010 to 61% in 2015. New solutions must allow continuous growth of access networks.

Currently implemented networks are composed by several domains like access, metro, and core. Within these layers there are too many IP routers and nodes that are costly in energy and packet delay due to the Optical– Electronic–Optical (O–E–O) conversions. Multilayer network compatible with Giga bits per second (Gbps) access rates are being aggressively developed, able to endure high scalability and flexibility, guaranteed end to end performance and survivability, energy efficiency and lower cost of ownership [3]. Due to the massive rollouts required at access networks, this domain presents additional technologic and economic challenges. Those additional challenges have increased the bottleneck at access networks to deliver enough bandwidth to end users. The introduction of optical fiber to the customer sites has been accepted as a solution to relieve the access bandwidth bottleneck and to cope with the ever increasing users' bandwidth demand [3][4].

To successfully deliver enough bandwidth to end users, the bottleneck at access networks must be released. As consequence, the introduction of optical fiber to the home (FTTH) or fiber to the customer sites (FTTx; stands for fiber to the x, where x stands for Curb, Building, Premises, etc.) has been accepted as a solution to relieve the access bandwidth bottleneck and to cope with the ever increasing users' bandwidth demand [5][6][7][8].

The FTTH Council announced a continuous global growth of all fiber networks [9]. The average broadband access network speed grew 97% from 2009 to 2010 [2]. Such a growth has been allowed by deployments of PONs (Passive Optical Networks) based FTTx. The total number of FTTH subscribers was about 38 million at the end of 2011 and is expected to reach about 90 million at the end of 2015 [10].

PON is a point–to–multipoint optical network, which connects an optical line terminal (OLT) at the carrier's Central Offices (COs) with several optical network units (ONUs) at the customer sites. This is done through one or more 1:N optical splitters. The success of PON relies on its high bandwidth, infrastructure cost sharing and its simple maintenance and operation, which results from the absence of electronic active components between the OLT and the

ONUs. As a consequence of the point to multi–point nature, PON's upstream channel requires a multiple access technology. Today's standards and deployments of FTTx are based on Time Division Multiple access PON (TDM–PON). TDM–PON uses a single wavelength for downstream (CO to users) and upstream (users to CO). Upstream and downstream channels are multiplexed in a single fiber through Coarse WDM (CWDM) technology standardized according to ITU (International Telecommunication Union) G.694.2 (CWDM spectral grid). TDM PON keeps the cost of access networks down, by sharing among all users the bandwidth available in a single wavelength. There are two main TDM–PON standards used for mass rollouts [9][11]:

- Ethernet PON (EPON) technology: specified by the IEEE (Institute of Electrical and Electronics Engineers) as the 802.3ah standard, which is widely deployed in United States of America and in Europe.
- Gigabit PON (GPON) technology: specified by the ITU–T G.984 standard, which is broadly deployed in Japan and South Korea.

However, TDM–PON cannot cope with future access networks' requirements regarding to aggregated bandwidth, reach and power budget [11]. To cope with this requirements, it has been widely accepted that the next step of evolution for PON architectures is the introduction of wavelength division multiple access in PON (WDM–PON) [6][10][11][12]. The WDM–PON approach assigns an individual wavelength to each ONU. This strategy allows the use of higher bandwidth for each ONU, longer reach, better scalability towards higher users' concentration, and provides transparent bit rate channels [11][12].

Hybrid schemes of WDM–PON are a current hot topic in the development of future proof networks. A combination of TDM and WDM over PON turns out into a hybrid optical network known as TDM–WDM–PON. In this scheme, a set of wavelengths is shared over time by different ONUs instead of being dedicated as in WDM–PON. TDM–WDM–PON improves the network resource's efficiency usage [13][14][15].

Another WDM–PON hybrid scheme arises from the possibility of transmitting subcarriers over a dedicated wavelength; this is the principle of Orthogonal Frequency Division Multiplexing with WDM–PON (OFDM –WDM–PON). This approach offers great capacity and applicability for the future passive optical networks [16].

A Combination of the Time Orthogonal Code Division Multiplexing (OCDM) and WDM over passive optical networks turns out into a hybrid optical network known as OCDM–WDM–PON. With OCDMA each ONU have a code word to differentiate their optical transmissions. It provides data transparency and security to end users, and it's an interesting access technique for future optical access networks [8][17].

The continuous growth of the users bandwidth demand is leading to more than 100 Gbps optical access systems [18]. This scenario implies that COs, supporting higher concentration of customers (with split ratio extended far beyond 1:64), will have to aggregate traffic in volumes reaching Tera bits per second (Tbps). Thus, there will be a higher congestion for management of the increasing bandwidth demand at the Metro–Access interface, and higher requirements of future applications on bandwidth guarantee and low latency.

In this paper, we present an accurate performance assessment of an hybrid WDM–PON architecture originally proposed in [19]. This architecture introduces a time–wavelength (t–λ) routing for an on–the–fly (optical bypass) routed, self–aggregating Metro–Access interface. The t–λ routing architecture, based on nonuniform traffic distribution in access networks, introduces optical bypass toward the most requested destinations. Its goal is to relieve the electronic bottleneck and simplify the Metro–Access interface.

Wieckowski et al. [19] have outlined the advantages of the t–λ routing architecture over WDM–PON. However, there is a situation in their simulation model that produces delay variations and packet reordering problems. The present enhanced version of t–λ routing architecture avoids those problems, thus allowing traffic to cope with the strict requirements of delay sensible traffic.

Simulation results obtained show that by using this enhanced t– λ routing architecture, the COs become congestion–free, a reduction of the network's power consumption is achieved, and the network is able to address different requirements of the traffic. Therefore, the present work proves that the use of optical bypass and traffic self–aggregation is a very attractive approach for future proof access networks.

The paper is organized as follows: Section II describes current Network domains. Section III summarizes the requirements for future optical networks. Section IV explains the expected evolution of optical access networks. Section V describes the $t-\lambda$ routing optical access network architecture. Section VI presents the related work of this paper. Section VII describes the simulation model developed and presents the simulation results. Section VIII concludes the paper and exposes future works.

II. TELECOM NETWORK DOMAINS

In general, Telecom Networks are divided into three major networks domains: core, metro and access as depicted in Figure 1. Core networks represent the backbone infrastructure covering nationwide and global distances. It aggregates and distributes traffic from large cities (as network nodes), countries and even continents. The core domain is usually based on a mesh interconnection pattern and carries huge amounts of traffic collected through the interfaces with the metro networks. Links in the core network could have a reach of a few hundreds to a few thousands of kilometers. In the backbone network, optical technologies are widely deployed based on IP over SONET (Synchronous Optical Network) / SDH (Synchronous Digital Hierarchy), IP over SONET/SDH over WDM (Wavelength–Division Multiplexing) and more recently IP over WDM [20].

The metro network domain is the part of a telecom infrastructure that covers metropolitan areas. This domain interconnects several nodes for aggregation of business and

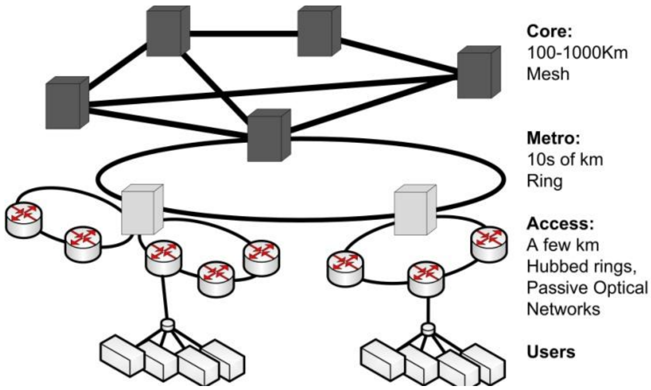

Figure 1. Telecom Network Domains [20].

residential subscribers' traffic. The metro represent the connection between the core domain and the access domain, allowing for Internet connectivity. Links in the metro could have a reach of a few tens to a few hundreds of kilometers. Metro domain is mostly based on SONET/SDH optical ring networks. Other commonly used metro networks are Metro Ethernet [21] and Metro WDM ring networks [22].

The access network connects business and residential customers to the rest of the network through their service provider Metro network. It aggregates and distributes traffic from several end user localities, covering areas of few kilometers. The Access is still dominated by several versions of Digital Subscriber Line (xDSL), but there is an increasing deployment of FTTH or FTTx, based on different flavors of PONs. Optical access networks are usually based on treelike topologies [11].

A. *Traffic Profile between network domains*

In general the Telecom network domains are interconnected by one or a few interfacing nodes (gateways), e.g., there is typically only one interconnection node between the Access and the Metro network, and between the Metro and the Core network. Due to our globalized society, it is well known by the academy that there is more traffic crossing through different network domains (remote or transit traffic), than traffic staying within the same network domain (local traffic) [23][24].

It has been observed that in a multiple interfacing scenario, traffic demands at IP routing nodes are not evenly distributed among all destinations. About four to five major destinations comprise the 80–95% of the outgoing traffic in the routers, and 50–70% of the traffic goes to one major destination [23]. This behavior can lead to insufficient capacity and traffic bottlenecks at specific points of the network. Thus, such traffic behavior must be considered in the design of new generation networks.

B. *Metro–Access Interface*

The fast penetration and the evolution of optical access networks will produce higher congestion at COs and Metro–Access interfacing nodes. Consequently, there will be a large pressure to deal with the increasing Quality of Service (QoS) demanded by future applications. Thus, future–proof, cost and energy efficient Metro–Access interfaces have been extensively investigated [19][25][26].

III. REQUIREMENTS FOR THE OPTICAL NETWORKS OF THE FUTURE

On the nearest future, the optical networks should support a major number of users and better traffic aggregation while keeping low power consumption. In this section, general future optical network's requirements are first presented. Later the specific requirements for access networks are highlighted.

A. *Future Optical Network's Requirements*

Currently implemented networks are composed by too many domains like access, metro, backhaul, outer core and inner core [3]. Within these layers there are many IP routers and nodes that are costly in energy and packet delay due to the O–E–O conversions and interfacing tasks.

It will soon be necessary the design of a multilayer network compatible with Gbps access rates, able to support high scalability and flexibility, guaranteed end to end performance and survivability, energy efficiency, and lower cost of ownership [3].

At the nodes level the legacy of O–E–O conversions have been changed for the idea of all optical networks (AON). Thus networks may move more functions to the optical domain to take advantage of the scalability of optics as the bit rate increases.

The Optical Network of the future should be remotely reconfigurable. It must be able to turn on and turn off wavelengths based on demand, and to change the optically routed paths without losing or delaying the traffic in the network. The solution to this requirement could be the introduction of Reconfigurable Optical Add Drop Multiplexer (ROADM), with All Optical Switches (AOS) [27]. Future optical network's requirements are summarized below in terms of network capacity, digital transmitter and receiver and the fiber design.

1) *Network Capacity*

There are three approaches for increasing the network capacity: increase the number of wavelengths supported by the fiber, increase the bit rate of every wavelength (spectral efficiency), and reduce the amount of signal distortion accumulated per distance unit. These approaches will be necessary in the nearest future, and they all require advanced modulations formats [27]. Modulations schemes like Quadrature Amplitude Modulation (QAM), Polarization Multiplexing and Orthogonal Frequency Division Multiplexing (OFDM) are currently being investigated. Phase Modulation Quadrature Phase Shift Keying (PM–QPSK) with coherent receivers is the main choice in the industry [28].

a) *Increasing the bit Rate per Wavelength.*

One method to increase capacity is the use of larger signal constellations like Dual Polarization Quadrature Amplitude Modulation (DP–MQAM) or DP–MQPSK. Using a modulation format with low Optical Signal to Noise Ratio (OSNR) requirement increases the achievable capacity.

However, data rate cannot be increased indefinitely by higher–order modulation because of the nonlinear Shannon's limit [29].

A challenge for increasing the bit rate of the wavelengths is the cost. As consequence of the development of high speed electronics, with each fourfold of the bit rate the cost of the associated transponder increments by a 2 or 2.5 factor [27].

b) Increasing the number of channels.

Instead of increasing the bit rate, a successful approach is to increase the number of wavelengths, reducing the inter channel spacing and possibly the bit rate.

Optical Orthogonal Frequency Division Multiplexing (O–OFMD) is a multiplexing scheme for high speed transmission. The high data rates are accomplished by parallel transmission of partially overlapped subcarriers at a lower data rate. The principle of this method is based on the orthogonality of the subcarriers frequencies, which allows overlapping the spectrum in an efficient way and eliminating the guard frequencies that were used in Optical Frequency Division Multiplexing (O–FDM) [30].

O–OFDM has the best potential of all the transmission technologies currently being investigated. The highest spectral efficiency and highest capacity reported for a WDM system in a single–core single–mode fiber was achieved using O–OFDM [16][31].

c) Nonlinearity Compensation.

The fiber capacity is limited by the nonlinearities. In the absence of noise, a single–channel signal is limited by self–phase modulation (SPM). Whereas Wavelength Division Multiplexing (WDM) systems are limited by cross–phase modulation (XPM) and four–wave mixing (FWM) [29].

The Nonlinear Schrodinger Equation (NLSE) is deterministic; it means that SPM, XPM and FWM could be compensated with digital signal processors (DSPs). As the DSP's capability improves, and systems seek to achieve highest capacity, nonlinearity compensation could become essential [29].

For the optical networks of the future, increasing spectral efficiency is the most important step as long as the reach in not sacrificed to the point of increasing regeneration costs [32]. Adding amplifiers seems reasonable, assuming Raman amplification is needed anyway, as long as the ROADM functionality and line stability are not sacrificed [32].

Reducing channel spacing appears to be the best long term solution for scalability assuming coherent detection systems as long as the performance is not sacrificed [32].

2) Digital Transmitter and Receiver

Next generation systems will continue with the trend that enabled the technologies of 100 Gbps. DSP will play an important role in the transmitter and receivers of the future optical networks, where advanced algorithms will be used to compensate fiber impairments [29].

a) Digital Coherent Receivers.

The advantage of digital coherent receivers stems on the ability to manipulate the electric field in the two signal polarizations [29]. Coherent receivers in conjunction with analog to digital converters ADC above Nyquist Rate, permit to manipulate the information contained on the digitalized waveform. Therefore, any information manipulated by hardware in the analog domain could be achieved in the digital domain by advanced software. One of the many benefits of coherent receivers is the correction of Chromatic Dispersion (CD) [29].

An additional benefit of digital coherent receivers is that it facilitates the channel demultiplexing. In traditional WDM systems, the channel of interest is selected by optical filters. In consequence, guard bands are required in WDM reducing the spectral efficiency [29]. With a digital coherent receiver, digital filters could be used for increasing the spectral efficiency.

Last but not least, a digital coherent receiver enables novel modulation formats e.g., OFDM [29].

b) Digital Transmitters.

DSP can also be used on the transmitter to generate the data above the Nyquist Rate, and Digital to Analog Converters (DAC) to acquire the signal to be sent to the receptor.

A software–defined optical system with DSP at both transmitter and receiver enables the most agile platform. It allows channel impairments to be compensated by powerful DSP algorithms, and enables new signal multiplexing and demultiplexing paradigms. In addition, the channel data rate, modulation format, and coding scheme can all be programmed by network management in response to channel conditions changes. Therefore, the network can become more flexible and tunable, allowing to route optical signals through several distances, fiber types, and different number of ROADMs in the path. Such flexibility is achieved by sensing the channel quality and adjusting the modulation format and coding scheme to provide reliable end–to–end connection at the highest data rate possible [29].

3) Fiber Design

The primary interest in optical networks is to increase system capacity. Even without nonlinearity, achievable capacity scales only logarithmically with power. A power–efficient method is to transmit information over parallel channels [29].

Future systems could require space–division multiplexing (SDM). The simplest SDM method is to use multiple fibers. This requires parallel transmitters, fibers, amplifiers, and receivers. System complexity will scale approximately linearly with capacity, so cost reduction per bit will only be achieved by minimizing the cost of inline amplifiers and transponders [29].

An alternative strategy is to have SDM within a single strand of fiber. Two schemes have been proposed: multicore fiber (MCF), and multimode fiber (MMF) [29].

B. Future Optical Access Network's Requirements

Due to the proximity of access networks with the end users, the access network presents additional technological and economic challenges. In consequence, those additional challenges had increased the bottleneck at access networks to deliver enough bandwidth to end users. The introduction of optical fiber to the customer sites has been accepted as the solution to relieve the access bandwidth bottleneck and to cope with the ever increasing users' bandwidth demand [4][33].

Requirements of network capacity, adaptation, scalability, energy efficiency, data integrity and other aspects will be summarized below.

1) Network Capacity

The future optical access network must be faster with increased bandwidth compared to current standards (e.g., EPON and GPON). Some authors expect that the minimum bit rate required in future PON architectures for downstream will be around 10Gbps, while the upstream requirement will be around 2.5 Gbps [34].

If ONUs shares the same channel for downstream and upstream, the bandwidth allocation will be dynamic. The dynamic bandwidth allocation allows operators to manage several kinds of traffic and different transmission bit rates upon requests. There are two kinds of bandwidth allocation mechanisms used in PON: status–reporting mechanism and non–status–reporting mechanism. In non–status–reporting, the CO continuously allocates a small amount of extra bandwidth to each ONU. The status–reporting mechanism and dynamic bandwidth allocation (DBA) are based on the Multi–Point Control Protocol (MPCP) specified in the IEEE 802.3ah standard [35].

Hybrid WDM–PON architectures such as TDM–WDM–PON, OCDM–WDM–PON and OFDM–WDM –PON allow to achieve higher transmission bit rate and to have more disposition of the bandwidth.

2) Adaption and Scalability

The massive deployment of fiber is limited by infrastructure investment. Hence, it is required to ensure future adaptation and scalability of the inversion. A major challenge for service providers is to keep simple operating procedures and ensure convergence of different networks. A migration to packet traffic transport platforms and the tendency towards a common access architecture facilitate the acquisition of new access technologies [36] .

The system must be flexible with the ability to be incorporated in sequential and modular way. Satisfy the needs of the operator in terms of network administration and implementation costs. The network must allow different types of user (e.g., business user, residential users, etc.) where each user may have different requirements and be subject to individual claims [36].

3) Costs and Energy Eficiency

The cost is the current limiting factor for massive deployments of optical access networks. There are different costs to consider in the networks: implementation, maintenance, infrastructure, network improvement and environmental impact. Energy efficiency has become a very important aspect for network design, due to increased operating costs related to energy consumption, increasing awareness of global warming and climate change. Due to its low power consumption, PON is considered as a green technology [9].

4) Integrity and Other Aspects

Redundancy includes automatic reconnection across redundant network elements, and should minimize the impact in case of failure. The system must be able to provide mechanisms for fault detection as monitoring and diagnosis for proper management. The network must also be able to locate and remotely provide a solution at the full extent of the network [36].

The systems must support heterogeneous access networks. The convergence of networks offers the possibility to optimize the total costs and to provide access technology solutions. In this context, fixed access backhauling and mobile backhauling must be considered [36].

Network operators are looking forward to simplify the network structure and reduce the number of access sites. Node consolidation would satisfy this requirement improving the overall cost efficiency of the network. Node consolidation is possible by increasing the reach (@100 Km) and the number of users supported by each access site [36].

Future access networks must provide data security and integrity to the customers. The terminal equipment should be simpler in terms of administration and configuration as possible (i.e., plug and play) [36].

IV. EVOLUTION OF OPTICAL ACCESS NETWORKS

In this section the evolution of optical access networks towards a future proof solution is presented.

A. TDM–PON

Time Division Multiplexing (TDM) is a multiplexing scheme that allows N users to share in time the bandwidth offered by the provider. In optical communications the shared resource is an assigned wavelength [13]. Currently, there are a few implemented standards of TDM based PON. However, the most employed are EPON (IEEE 802.3ah), principally adopted in Asia, and GPON (ITU–T G.984) in Europe and North America [13].

EPON transports Ethernet frames in PON, this standard combines the low costs of the Ethernet devices with the passive optical components of PON. IEEE 802.3 (Ethernet in the First Mile) in 2004 established the standard for symmetric traffic at 1 Gbps, for a 10 to 20 km link, with 16 ONUs per each OLT.

GPON transmits TDM data frames, at a data rate of 2.5 Gbps for the downlink and 1.25 Gbps for the uplink.

With the higher bandwidth requirements, it was necessary to implement a 10 Gbps standard (10 GE–PON). However, as the number of users and the bandwidth requirements increase, the TDM–PON architecture becomes insufficient.

B. WDM–PON

A straightforward and widely accepted upgrade for TDM–PON is the introduction of wavelength division multiple access in PON [6][10][11][12]. The WDM–PON approach assigns an individual wavelength to each ONU. This strategy allows the use of higher bandwidth for each ONU, longer reach, better scalability towards higher users' concentration, and provides transparent bit rate channels

[11][12]. WDM–PON provides security and integrity to end users, and it facilitates network upgradeability for enhanced future–proofing.

The high cost of WDM–PON has made it less attractive for implementation. To date, the only commercially available WDM–PON system has a cost roughly twice of EPON or GPON [10].

The GigaWaM Project aims to develop essential optical subsystem components required for a future–proof WDM–PON broadband access system providing each end user with up to 1 Gbps bidirectional data bandwidth. A main goal of GigaWaM Project is to achieve a target cost below that of a typical TDM–PON implementing 70 Mbps per user [10].

C. Hybrid WDM–PON

In this subsection, three hybrid access technologies that provide improved capacity, scalability, and spectral efficiency are presented. Such technologies are envisioned to meet the requirements of future services and applications.

Even though high speed digital signal processors are in continuous evolution, the photonic circuits still an immature technology. Therefore, practical implementation of Hybrid WDM–PON architectures represents a major challenge due to the complexity and costs in both photonics and high speed electronics hardware [8].

1) TDM–WDM–PON

A Combination of TDM and WDM over PON turns out into a hybrid optical network known as TDM–WDM–PON. In this scheme a set of wavelengths are shared over time by different ONUs instead of being dedicated as in WDM–PON. This architecture improves the efficiency of the network resources [13].

The design and implementation of this architecture present new challenges, because the network should be dynamic, in the sense that each ONU must tune into the different wavelengths of the OLT. Also, the transmission and reception of the TDM packets shall be configurable.

An architecture based in TDM–WDM–PON is proposed in [13] using new modulation schemes. On the downlink, Phase Shift Keying (PSK) is used. On the Uplink the signals are remodulated with On–Off Keying (OOK) using a delay Interferometer (DI), and an NxN cyclic Arrayed Wave guide Grating (AWG). In this scheme, the interference between both, uplink and downlink is decreased. Also, only one instead of two dedicated DI are required on each ONU. The architecture was demonstrated at a data rate of 10 Gbps on the downlink and 1.25 Gbps on the Uplink.

High capacity and long reach architectures have been demonstrated [14][15]. A TDM–WDM–PON with capacity of 8192 ONUs, symmetric traffic of 320 Gbps and links of 135.1 km length was demonstrated [14]. The configuration of the network consisted of 32 wavelengths in the downlink and another 32 in the uplink, with 50 GHz spacing. The transmission was in burts at 10 Gbps each. The total capacity achieved was 256 ONUs per wavelength. A similar architecture with capacity of 16384and 100 km reach is demonstrated in [15].

2) OFDM–WDM–PON

OFDM is a multiplexing scheme that offers a major spectral efficiency due to the use of orthogonal frequencies for data transmission. It has been demonstrated that N carriers could be transmitted over the same frequency band without interfering each other [16]. With respect to other multiplexing schemes like Single Carrier Multiplexing (SCM) or Frequency Division Multiplexing (FDM), OFDM–WDM–PON is more efficient, because it eliminates the guard bands between the different channels.

An OFDM channel offers many possibilities for modulation formats, such as amplitude, phase, polarization and intensity. For this reason, depending on the type of the modulation format selected, it is possible to obtain different reception schemes. Among these architectures are: amplitude modulation Optical OFDM (O–OFDM), optical modulation with Coherent detection (CO–OFDM), and All Optical OFDM (AO–OFDM).

OFDM is an option that may offer a bigger capacity for the optical fiber systems. There are multiple variations for the implementation of optical OFDM. In the simplest form, it is possible the transmission of multiple dedicated optical subcarriers over the passive optical network, this is known as OFDM–PON. A more complex scheme is to provide multiple access by sharing the subcarriers as needed. Therefore, subcarriers are allocated to different users in different slots of time; this is the case of TDM–OFDMA–PON. Last but not least important, there is the possibility of transmitting the subcarriers over a dedicated wavelength; this is the principle of OFDMA–WDM–PON. This option offers the biggest capacity and applicability for the future optical networks [16].

Record of 1.92 Tbps (40λ × 48Gbps/λ) coherent DWDM –OFDMA–PON without high–speed ONU–side was demonstrated over 100km straight Standard Single Mode Fiber (SSMF) with a 1:64 passive split [37]. Novel optical–domain OFDMA sub–band selection, coherent detection, and simple RF components are exploited. As an experimental verification of a next–generation optical platform capable of delivering 1 Gbps to 1000 users over 100km, this is a promising architecture for future optical Metro– Access consolidation.

The proposed DWDM–OFDMA–PON architecture consists of optical carriers separated by a 50 GHz band for both the uplink and the downlink, without the use of high speed ONUs in the downlink, because of the coherent detection. The optical channels contain four subcarriers at 12 Gbps data rate each. The result is 48vGbps–λ speed. For the DS/US 40 wavelengths on the 1532.29–1563.45nm range are used [37].

Symmetric 1.2 Tbps DWDM–OFDMA–PON is demonstrated in [31] over a SSMF with a 1:32 passive splitter. The proposed system supports 800 ONUs with reduced complexity and it could be a solution for Metro–Access consolidation.

The proposed architectures in [16][37] are resumed in [38], where the future terabit optical networks based in DWDM–OFDMA–PON are shown. N subcarriers are generated and then modulated by an optical continuous wave. All the wavelengths are transmitted with an AWG, and an Optical Single Side Band (OSSB) signal is produced with an interleaver (IL). The transmission is made through a SSMF. After X kilometers a local exchange is made, where the signals are amplified and rerouted through an AWG, and DS/US pairs are retransmitted to the ONUs. Once the signal arrive to the destination each ONU tune in to the subcarrier of interest. On the uplink the subcarrier is mapped back to the band from where it was selected, and then is transmitted in the wavelength of US. The signals from different ONUs are combined and received coherently by the OLT. This architecture supports λ x N without dispersion compensation.

A symmetric transmission on baseband and 4–Amplitude Shift Keying (ASK) Fast OFDM (F–OFDM) was realized for colorless ONUs [37]. The difference between this scheme and the one showed in [38] is that the DS wavelength is reused for the US transmission, in consequence the ONU is colorless. The achieved capacity was 160 Gbps (16λx10Gb/s) in symmetric traffic.

All the presented architectures show a trend to metro access integration, since the main goal is to achieve the highest transmission speed and a long reach.

3) OCDM–WDM–PON

A Combination of the OCDM and WDM over passive optical networks turns out into a hybrid optical network known as OCDM–WDM–PON.

With OCDMA each ONU has a code word to differentiate their optical transmissions. At the ONUs an optical operation encodes each bit before transmission. At the receiver, an inverse decoding operation must be performed to retrieve data. OCDMA has a scheme similar to WDMA, offering point to point virtual links over one physical point to multipoint architecture, providing data transparency and security to end users. OCDMA supports a higher number of users than TDMA asynchronously, eliminating the processing and network overhead required for synchronization of TDMA. Thus OCDMA is presented as an interesting access technique for the optical access network of the future [8][17].

OCDMA–WDM–PON has unique features as full asynchronous transmission, low–latency access, demand –driven capacity, and data integrity. Using OCDMA–WDM–PON it has been shown experimental speeds higher than standard 10G–PON [39]. The authors in [39] included a multiport device encoder and decoder with the ability to generate and process calculations with multiple codes on multiple wavelengths. The multiport allows multiple users to connect and thus the cost of infrastructure can be shared between multiple users. The implementation of an 8x8 multi–port using 4 wavelengths, each at 40 Gbps, permits to achieve a maximum transmission speed of 2.56 Tbps (40Gbps x 8λ x 4 OC x 2 PM), over a 50 km fiber.

Mechanisms such as VPN (Virtual Private Network) in OCDMA system can be generated with Walsh coding. Some studies has proposed the creation of VPN using keys to feed each of the PRBS (Pseudo Random Bit Sequence) producing non–orthogonal sequences with larger spacing, making it more attack resistant [40].

The OCDM–WDM–PONs suffer from a lack of transitional models that take into account legacy systems [7].

V. Time–Wavelength ($t-\lambda$) Routing Optical Access network Architecture

In order to design a future proof optical Access Network, the nonuniform traffic profile represents an interesting useful behavior to be exploited by architectures with optical bypass. Optical bypass is a technique to avoid the electronic routing tasks like: optic–electronic conversions (O–E), error correction algorithms, electronic buffering, electronic processing, and electronic–optic conversions (E–O). Therefore, Optical bypass will reduce power consumption and node complexity.

The t–λ routing optical access architecture exploits the traffic profile of Metro–Access networks to introduce optical bypass and passive self–aggregation of Metro–Access traffic [19]. The goal of the architecture is to use the nonuniform traffic distribution of access networks to select the major traffic portion to transmit it through all optical channels (on–the–fly routed). In consequence, the t–λ routing optical access architecture reduces the electronic traffic aggregation and routing tasks.

The selection of the traffic portion, which will be optically bypassed relies on the analysis and evaluation of a multiple gateway traffic–distribution [23]. Based on this analysis up to 70% of the traffic generated in the access networks is destined to the Metro–Access interfacing node (called major destination). In consequence, the t–λ routing approach is designed to perform optical bypass and traffic self– aggregation at COs of the major destination traffic (up to 70% of all traffic generated by the users). The minor destination traffic (local traffic) is sent through electronically routed channels using common stop–and–forward policies.

The underlying idea of the t–λ routing approach is presented in Figure 1 using a PON to connect N=3 ONUs.

The architecture arranges ONUs in groups that are equal to the number of wavelength in the t–λ frame (3 wavelengths in the case depicted in Figure 2). For each PON the COs assign a specific wavelength/channel to perform the optical bypass (passive channel) for upstream major traffic. To avoid wavelength interference at the COs network, the wavelength assignment must ensure different passive wavelengths for each PON sharing links in their path towards the major destination.

Based on the requirements of future access networks, the t–λ routing architecture employs colorless reflective ONUs. Reflective ONUs allow providers to have centralized control over the access network at the COs. The COs send Continuous Wave (CW) seed light to ONUs based on the t–λ frame. Each ONU sorts packets at the customer sites on the basis of their destination. Major traffic is introduced in a buffer associated with the passive wavelength (passive channel). Minor destination traffic is arranged in other buffers associated with electronically routed channels.

Colorless reflective semiconductor optical amplifier modulators (RSOA) are used to transmit data by modulating

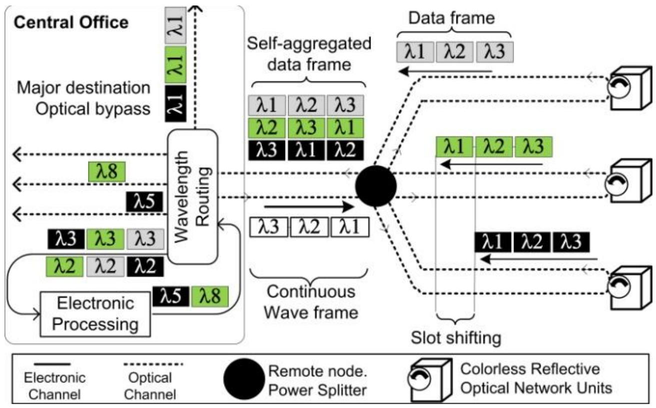

Figure 2. Underlying idea of the time–wavelength assignment and Central Office (CO) schematic diagram, for time–wavelength routed architecture to provide on–the–fly routing to Major destinations. CW: Continuous Wave.

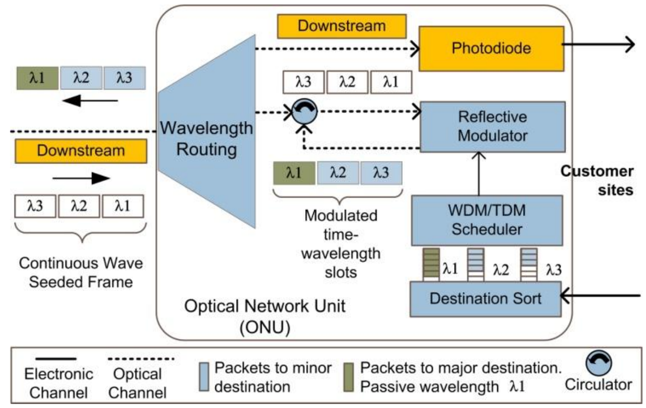

Figure 3. Basic Reflective Optical Network Unit (ONU) scheme. Downstream and Upstream channels coming from the Central Office (CO) are separated by a wavelength filter. The seeded upstream Continuous Wave (CW) is modulated and reflected back to the CO by the colorless reflective semiconductor optical amplifier (RSOA). Incoming customer traffic is sorted by destination in specific buffers.

the CW seeded by COs [25][41]. Major destination traffic only modulates the predefined passive wavelength.

A collision free optical self–aggregation will be achieved by assuring that the upstream signals arrive at the remote node (splitting and combining point) properly adjusted in time based on the t–λ frame (see Figure 1). In consequence, each wavelength at the CO will contain self–aggregated data from several ONUs. At COs the self–aggregated major destination traffic is optically routed on–the–fly (optical bypass). The rest of the wavelengths are sent to local processing units for destination inspection, routing and forwarding (electronically routed channels). As shown in Figure 1, the CO assigns λ1 as passive channel. Hence λ1 is self–aggregated and on–the–fly routed towards the major destination.

VI. Related Work

In a former performance evaluation, the authors have shown the advantages of t–λ routing architecture over a conventional WDM–PON. It was therefore proposed as solution for a transparent and self–aggregating Metro–Access integration architecture [19]. In the former evaluation the architectures were assessed by means of dedicated discrete step–based simulation models, with a Poisson process for traffic arrivals and packet Loss Rate (LR) as the performance metric [19]. In the present work, an event–based simulation model has been developed. The developed model introduces some enhancements in relation with the previous architecture.

A. *Excess Traffic in passive channels*

In the simulation model developed in the prior evaluation, the excess traffic in passive channels was distributed to electronically routed channels. Excess traffic in passive channels constitutes major traffic (traffic destined to a major destination) arriving at ONUs, which produces overflows of buffers associated with the passive channels (passive buffers). Therefore, upon passive channel overflows the major excess traffic is electronically routed towards the major destination. This approach allows to use passive channels resources at the maximum and to distribute major excess traffic trough the electronically routed channels.

LR was the only performance metric used in the former evaluation, and advantages of the t–λ routing architecture over WDM–PON have been shown [19]. But customers are demanding applications with requirements beyond bandwidth and loss rate. According to Cisco's Visual Networking Index, globally Internet video traffic will grow from 40% of all consumer's Internet traffic in 2010 to 61% in 2015 [2]. Inelastic traffic applications especially video–related traffic hava been flooding the networks, and future optical access networks must address the requirements of low delay and jitter.

There is a negative behavior in the t–λ routing architecture if the excess traffic in passive channels is distributed through electronically routed channels. In general, using this approach the packets will arrive at major destination with high delay variations. Such delay variations lead to constant packet reordering at the major destination. Packet reordering can be compensated with buffering at the price of an additional delay. In future optical access networks (managing traffic volumes of Tera bits per second), the buffer size for packet reordering could be prohibitive. We analyze two types of Internet traffic for discussing the traffic behavior and the consequences of this approach:

1) Inelastic traffic (voice, video–related and time sensitive traffic)

The packet reordering compensation adds additional delay. Thus, inelastic traffic will be most likely to be discarded, because even when the destination is reached, it could not meet the low delay and jitter requirements. Additionally, this traffic (most likely to be discarded) will compete inside the t–λ routing architecture for resources with minor destination traffic.

2) Elastic traffic (web, mail)

TCP (Transport Control Protocol), the standard Internet transport protocol for non delay sensible traffic, has been proven to be packet reordering–sensible. TCP produces unnecessary traffic retransmission under constant packet reordering, and can lead to bursty traffic behavior, thus increasing the network overload [42].

Based on the negative behavior in elastic and inelastic traffic produced by the use of the approach presented in [19], in this work we use a different approach for excess major traffic.

The t–λ routing architecture has been proposed as a solution for a transparent and self aggregating Metro–Access integration. Considering that inelastic traffic will flood future networks, we developed an enhanced t–λ routing architecture model. In the enhanced version, the excess traffic in passive channels is dropped at the ONUs. In consequence, the delay variations and the packet reordering problems are avoided.

By dropping the excess traffic at ONUs the electronic routing tasks are reduced, avoiding the electronic bottleneck at COs (i.e., it moves the network bottleneck of major traffic from the COs to the ONUs). The considered approach in the proposed enhanced t–λ routing architecture is that if some packets should be discarded by a network bottleneck, it is better that happen as soon as possible.

B. Routing algorithm

Routing in the network model implemented in [19], is based on the Dijkstra algorithm. For each network node, all possible paths to other nodes are calculated. Next, the shortest paths to all achievable destinations are selected. The shortest path in the Dijkstra algorithm is the smallest weight path, so it potentially introduces the smallest delay and losses. The unique names of destinations with the "best" next hops are written into the routing table. Thus, the Dijkstra algorithm was implemented to consider only one shortest path even if there is more than one equal weight shortest path to any particular destination.

The proposed enhanced routing approach considers all different equal weight shortest paths and evenly shares the traffic between them, performing a network load balancing. Load balancing improves network performance by reducing losses caused by buffer overflows and by reducing the average packet end–to–end delay due to the reduction of the time that packets spent in the buffers.

In the developed model, the nodes manage routing tables based on the OPNET Modeler DJK package. The DJK package is based on a variation of Dijkstra algorithm to generate the set of shortest paths for each node [43].

VII. Performance Assessment of WDM–PON vs. $t-\lambda$ Routing Optical Access network

In the present work, the enhanced t–λ routing architecture and a conventional WDM–PON architecture (as reference) have been evaluated by means of simulation models developed in OPNET Modeler. OPNET Modeler is an event–based state–of–the–art network system modeling and simulation environment [43].

A. Performance metrics

In the related work, the authors had only considered LR to assess the architectures. Nevertheless, the delay metrics had gained more relevance to offer today services. Globally, Internet video traffic is expected to grow from 40% of all consumer Internet traffic in 2010 to 61% in 2015 [2]. In the present work, the developed simulation model in OPNET Modeler introduces *LR*, end–to–end delay and average buffer delay as performance metrics.

1) Loss Rate LR

It is the relation between lost packets and sent packets (1). When a specific node, is congested the packet loss is unavoidable. Based on *LR* we determined if the t–λ routing architecture can effectively avoid the packet loss due to the electronic routing bottleneck (the cause of network congestion).

$$LR = \frac{Packets_{lost}}{Packets_{sent}} \quad (1)$$

2) End–to–End delay EED

It is the time difference between the time instant when the first bit of a packet arrives at an ONU and the time instant when the last bit of a packet is received at its destination. Packet EED is calculated as the summation of buffering delay, processing delay and transmission delay. The EED is an important metric for the performance assessment of optical bypass in the t–λ routing architecture, and the benefits of avoiding electronic routing at COs.

3) Average Buffer Delay

Defines the average time experienced by each packet into a specific buffer. The buffer delay is the time difference between the time instant when the first bit of a packet arrives at a specific buffer and the time instant when the last bit of a packet gets out of the buffer. It is calculated based on (2).

$$\overline{Buffer\_Delay}_i = \frac{1}{N_i}\sum_{n=1}^{N_i} Buffer\_Delay_n \quad (2)$$

Where $\overline{Buffer\_Delay}_i$ is the average delay experienced by the packets that went out in the time window i. N_i is the number of packets that went out of the buffer in the time window i. $Buffer\_Delay_n$ is the delay experienced by the n^{th} packet in the i^{th} time window.

The variations in the EED experienced by the packets are consequence of medium access, electronic routing and aggregation tasks (processing and buffering delay). Thus buffer delay is an interesting useful metric, which allows determining bottlenecks and congestion points in the evaluated networks.

B. Traffic model

At ONU nodes a traffic generator models incoming traffic. The traffic is generated based on probabilistic distributions for: packet inter–arrival times, packet length and packet destination.

The traffic model used in [19] was Poisson, with fixed length. In the present work a more accurate traffic model was introduced for a more accurate performance assessment.

At ONU nodes a traffic generator can generates incoming traffic with several short range dependence distribution (e.g., Poisson) and long range dependence distribution (e.g., Fractal Point Process), using a variation of the OPNET simple source and the raw packet generator respectively [43]. It is well known that Internet traffic presents self–similar behavior, which reproduces the burstiness of Internet traffic [44]. Hence, for the performance evaluation the traffic generator was configured to generate incoming traffic with self–similar inter–arrivals times.

C. Validation of t–λ Routing Architecture Model

For validation purposes the simple topology presented in Figure 4 was used.

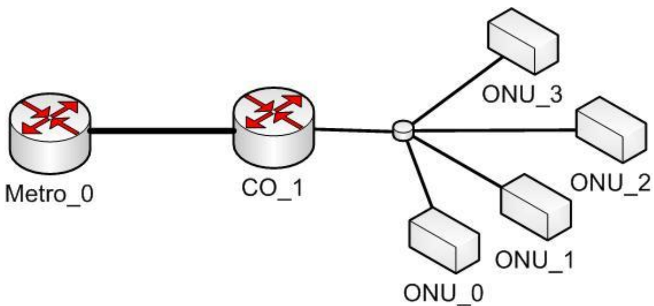

Figure 4. Validation scenario. Four Optical Network Units (ONU) connected through a Passive Optical Network to a Central Office (CO_1), the CO_1 is connected to the Metro–Access interfacing node (Metro_0).

The validation scenario consisted in a PON based on the t–λ routing architecture connected to $N = 4$ ONUs and the CO_1 was connected to the Metro–Access interfacing node (Metro_0).

1) Scenario Configuration

The t–λ frame period was set to $T_{frame} = 125\ \mu\ seconds$ long. Therefore, each t–λ slot time was set to $T_{Slot} = \frac{T_{frame}}{4} seconds$. There were only two possible destinations in the network: CO_1 and Metro_0. Optical bypass was performed for traffic destined to Metro_0 (through the t–λ passive channel). ONU–CO_1 links had four WDM channels to accomplish the t–λ frame, and a transmission rate of $R = 155.520\ Mbps$ (OC3). The CO_1–Metro_0 link was configured with two WDM channels at $R = 155.520\ Mbps$. CO_1 and Metro_0 processing capacity were in line with the transmission links rate $C = 155.520\ Mbps$. The buffer size was set to introduce a maximum buffer delay of $10\ msec$ based on the following equation:

$$Buffer_{length} = R \cdot Max\_buffer\_delay \qquad (3)$$

The traffic inter–arrival time was set to present self–similar properties generated with a Power ON–Power OFF model with Hurst parameter H= 0.8. Packet length was exponentially distributed with a mean of $1024\ bit$. Simulation time was set to $100\ sec$.

2) Theoretic Analisys

Each ONU had $N = 4$ buffers associated with each t–λ channel. Because of the time division multiplexing, in average each ONU experienced a transmission rate of $R_i = \frac{R}{N}\ bps$.

The t–λ routing architecture was proposed to introduce the optical bypass of only one passive channel per each CO [19]. In consequence, for each ONU the optical bypassed traffic (destined to Metro_0) experienced in average a transmission rate of $R_i = 0.25 \cdot R\ bps$. While the rest of the traffic (destined to CO_1) experienced in average a transmission rate of $3R_i\ bps$.

Even though the CO_1 – Metro_0 link had 2 WDM channels at $R\ bps$, the t–λ routing architecture used only one WDM channel for traffic destined to Metro_0. Channel sub utilization was expected due to the lack of packet segmentation to fill up the t–λ slots in the simulation model.

The developed model considered error free optical links. Therefore, as CO_1 and Metro_0 processing capacity were in line with the transmission rate, losses were only produced by buffer overflow.

There was a major bottleneck at the passive channel of the t–λ routing architecture. When the traffic destined to Metro_0 exceeds arrivals at $R_i = 0.25 \cdot R\ bps$ the buffer associated with the passive channel overflowed and in consequence, packets were lost.

3) Simulation Results

Figure 5 depicts the results of Loss Rate (*LR*) vs. Offered Traffic (*A*) for four different traffic distributions. The distributions ranges from 25% of *A* destined to Metro_0 (75% destined to CO_1) to 100% of *A* destined to Metro_0.

a) Case 1: 25% of A destined to Metro_0 and 75% of A destined to CO_1

In this case, the t–λ routing architecture perceived a uniform distribution of A in the four t–λ channels. When $A < 80\%$ there were no buffers overflow because there is none overloaded channel. For $A > 80\%$ the four channels started to lost packets due to buffers overflow. When the network was fully loaded $(A = 100\%)$ the four channels were overloaded and the overall *LR* was 20%. This 20% of *LR* was consequence of the channel sub utilization. Therefore, there was a 5% of capacity in each channel being lost due to the channel sub utilization.

b) Case 2: 50% of A destined to Metro_0 and 50% of A destined to CO_1

The 50% of *A* destined to CO_1 was transmitted by three not overloaded channels. Those three channels handled without overloading up to 60% of *A* (20% per each channel). For $A > 40\%$ the passive channel started to get overloaded. For $A = 100\%$ there was 30% of *LR*, due to only 20% of *A* was transmitted through the passive channel.

c) Case 3: 75% of A destined to Metro_0 and 25% of A destined to CO_1

In this case, 25% of *A* was transmitted loss–free towards CO_1 through 3 t–λ channels. When $A = 100\%$, from the 75% of *A* destined to Metro_0 the passive channel was only

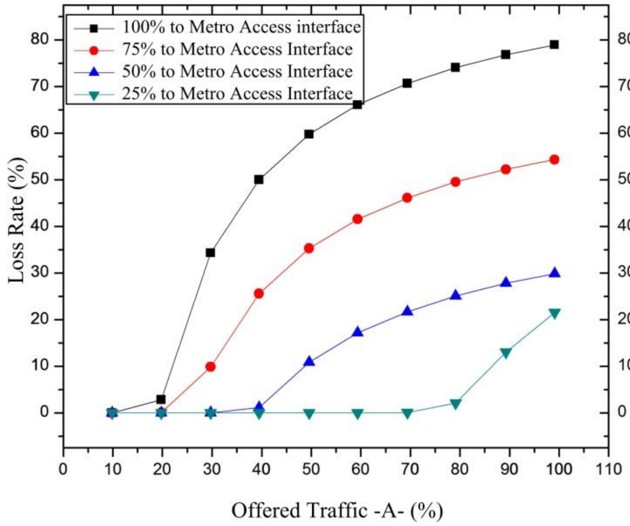

Figure 5. Loss Rate (LR) vs. Offered Traffic (A) for the t–λ Routing Architecture. The four curves represents diferent traffic distributions.

able to transmit up to 20% of A. In consequence, for $A = 100\%$ LR was expected to be 55%.

d) Case 4: 100% of A destined to Metro_0

For this case, when $A > 20\%$ the LR started to increase because the passive channel was overloaded. For $A = 100\%$ a 80% of LR was expected.

Figure 6 presents the curve of Carried Traffic (A_c) vs. Offered Traffic (A) for link ONU_0 – CO_1 using the first case of traffic distribution (25% of A destined to Metro_0 and 75% of A destined to CO_1). In this case the Offered Traffic was uniformly distributed through the four t–λ channels. For $A < 80\%$ the curve obtained is a straight line where $A_c = A$. When $A \geq 80\%$ the four channels started to get overloaded and their associated buffers started to overflow. Therefore, the Carried Traffic A_c had a limit of 80%. These results were consistent with the analysis presented with Figure 5.

Figure 7 depicts the average Buffer Delay for the associated passive channel of ONU_0 using the first case of traffic distribution (25% of A destined to Metro_0 and 75% of A destined to CO_1). There are six curves corresponding to $A = [100\%, 90\%, 80\%, 70\%, 60\%, 10\%]$.

To evaluate the results of Figure 7, it has to be remember that each channel perceived in average a transmission rate of $R_i = 0.25 \cdot R\ bps$, but 5% of the channel capacity was lost by the channel sub utilization. Therefore, the buffer of each channel must be overflowed for $A > 80\%$.

In Figure 7, for $A \leq 80\%$ there is a proportional increase of the average Buffer Delay related to A. For $A = 80\%$ the mean value of the average buffer delay was 1.17 $msec$. For $A > 80\%$ the mean value of the average buffer delay was 11.58 $msec$; showing that the buffer was overflowed.

The maximum buffer delay was set to 10 $msec$. However such maximum delay was defined by (3), where no channel sub utilization was considered. However, the channel sub utilization made packets to stay more than 10 $msec$ at the buffers.

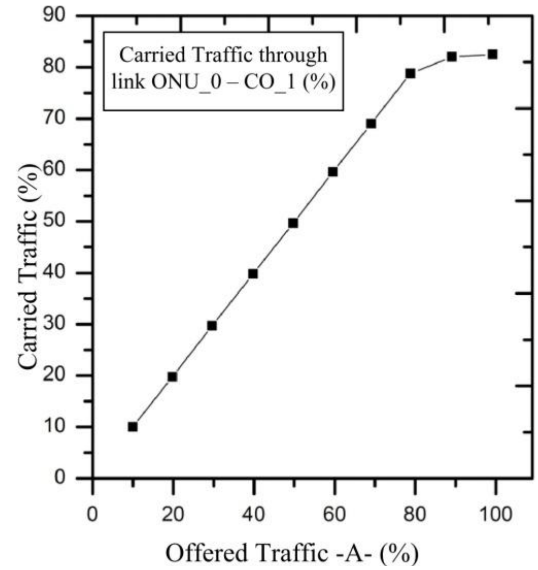

Figure 6. Carried Traffic (A_c) vs. Offered Traffic (A) for link ONU_0 – CO_1 using the first case of traffic distribution (25% of A destined to Metro_0 and 75% of A destined to CO_1).

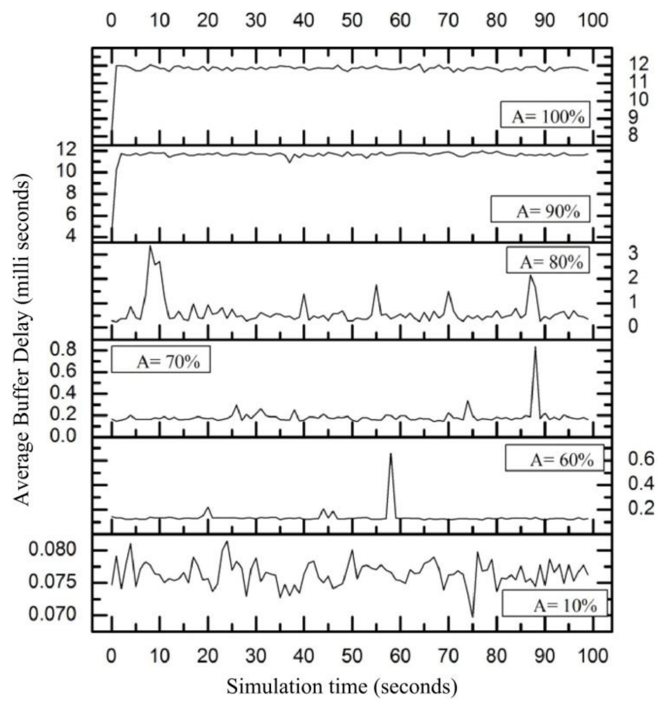

Figure 7. Average Buffer Delay for the associated passive channel of ONU_0 using the first case of traffic distribution (25% of A destined to Metro_0 and 75% of A destined to CO_1). Results are presented for five values of Offered Traffic $A = [100\%, 90\%, 80\%, 70\%, 60\%, 10\%]$.

D. WDM–PON Model Validation

For validation of developed WDM–PON model, the simple topology presented in Figure 4 was used with the same configuration parameters. Thus, allowing for model validation and performance comparison between both architectures.

1) Theoretic Analisys

In WDM–PON, a WDM channel was dedicated to each ONU, i.e., Offered Traffic perceived in average a transmission rate of $R\ bps$. Therefore, there must be no buffer overflow at ONUs even when $A = 100\%$.

The processing capacity of the nodes was in line with the transmission rate. In consequence, CO_1 was capable of processing all arriving packets, presenting a maximum for $N = 4$ ONUs of $4R\ bps$.

There must be a bottleneck at the CO_1 – Metro_0 link because there were only 2 WDM channels at $R\ bps$. Thus, at Metro_0 can arrive traffic at a maximum of $2R\ bps$. When traffic destined to Metro_0 arrived at CO_1 at more than $2R\ bps$ buffers started to overflow and the loss rate started to increase.

2) Simulation Results and Analysis

Figure 8 shows gathered results of Loss Rate (*LR*) vs. Offered Traffic (*A*). Results are presented for three cases of traffic distribution.

a) 50% of A destined to Metro_0 and 50% of A destined to CO_1

The curve associated with this case shows that there was no packet loss. As it was expected only when at CO_1 arrives traffic destined to Metro_0 at more than $2R\ bps$ there will be packet loss.

b) 75% of A destined to Metro_0 and 25% of A destined to CO_1

In this case, the bottleneck imposed by the 2 WDM channels started to produce buffer overflows for $A \geq 70\%$. For $A \geq 70\%$ the ONUs were generating traffic destined to Metro_0 at more than $2R\ bps$. For $A = 100\%$ there was a *LR* of 25% because 75% of the offered load requested the CO_1 – Metro_0 link and it only supported 50% of the offered load ($2R\ bps$).

c) 100% of A destined to Metro_0

It can be seen that for $A > 50\%$ the *LR* curve started to grow, as was expected. When 100% of generated traffic was destined to Metro_0, the 2 WDM channels of CO_1 – Metro_0 link only supported up to 50% of the load without packet loss.

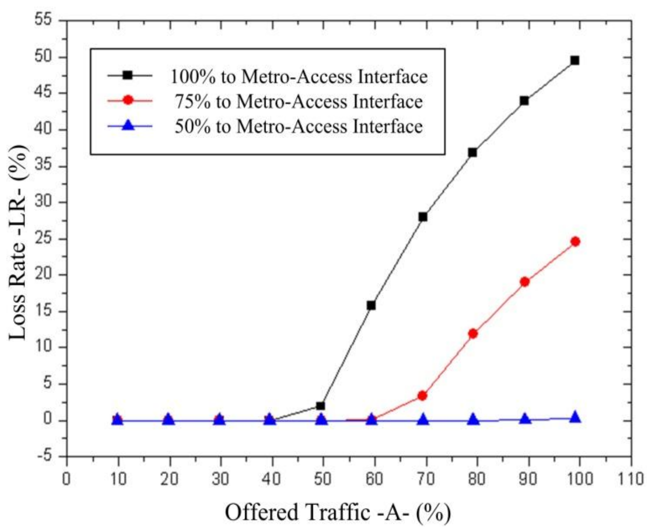

Figure 8. Loss Rate (LR) vs. Offered Traffic (A) for the WDM–PON Architecture. The three curves represents diferent traffic distributions.

E. Performance Assessment

Figure 9 presents the simple network topology used in the simulation experiments. This topology was selected in order to establish some comparison with the former evaluation [19]. It consisted of five COs with four ONUs connected to each CO and a Metro–Access Interfacing Node (MN) as major destination. The COs were connected to each other in a ring arrangement. Just one CO was connected to the MN.

1) Scenario Configuration

The set up of the performance assessment scenario was as follow. Transmission Rate was set at $R = 125\ Mbps$ (one magnitude order below EPON standard rates). The processing rate of the nodes was set to be on line with the transmission rate. Buffer sizes were assigned to limit the maximum buffer delay at $1\ msec$ in relation with the transmission rate; based on design considerations assumed in [45].

The applied traffic model had self–similar arrivals processes with Hurst parameter H ~ 0,74; based on empirical traffic evaluations [44]. The traffic distribution was the same as used in the former evaluation. It was taken from a multiple gateway traffic assessment, where 70% of A was destined to the major destination (i.e., the MN) and the rest was equally distributed among the minor destinations (i.e., the five COs) [19][23].

The t–λ frame period was set to $T_{frame} = 125\ \mu\,sec$; compatible with the Synchronous Digital Hierarchy (SDH).

Each frame is composed by four t–λ slots (same number as ONUs connected to each CO). The time slots were assigned to specific wavelengths, and the wavelengths were associated with the MN as the major destination and with the COs as minor destinations.

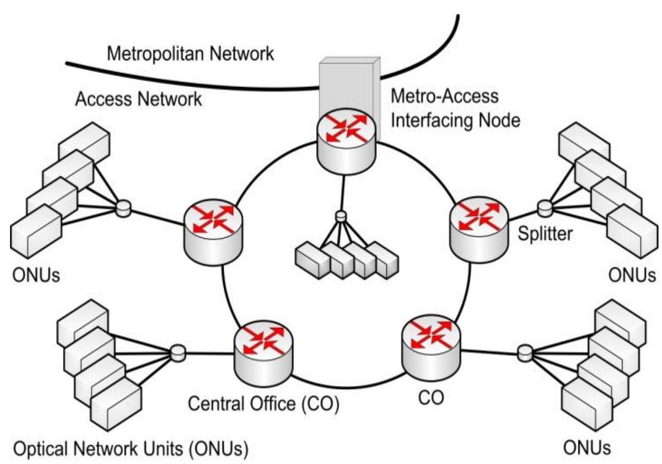

Figure 9. Simple Access network topology used for the performance evaluation, based on a ring interconection of COs. The Metro–Access interfacing Node (MN) represents the major destination (for the performance assessment up to 70% of traffic was destined to MN).

In conventional WDM–PON, each ONU had its own dedicated wavelength, which is terminated at the CO, i.e., no passive channels provided.

2) Simulation Results and Analysis

Performance assessment was carried out using a worst case electronic bottleneck scenario; i.e., up to 70% of the offered traffic was destined to the major destination (MN). As there were four ONUs per each CO (see Figure 9), the t–λ frame was composed by four time shared wavelengths. Only one wavelength was optically bypassed towards the major destination per each CO (i.e., one on–the–fly routed path established from CO to MN). In this way, each ONU perceived up to 25% of the transmission rate to send traffic through the passive channel, producing fast overload of the passive channels.

Figure 10 shows the simulation results for *LR* and *EED* vs. A for the enhanced t–λ routing architecture and the conventional WDM–PON as reference. As can be observed in Figure 10, the conventional WDM–PON has a superior performance, based on *LR*, because of the expected fast overload of passive channels in the enhanced t–λ routing architecture. However the *LR* in WDM–PON tends to worse when A increases (higher degree of congestion in the network) as a consequence of the COs' electronic bottleneck.

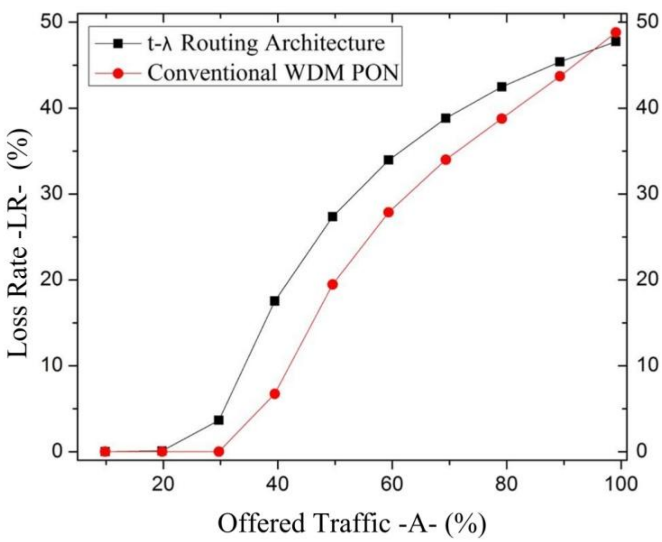

Figure 10. Loss Rate (*LR*) vs. Offered Traffic (*A*); for 70% of *A* destined to Metro Node (MN).

Figure 11 presents the *EED* experienced by the enhanced t–λ routing architecture, based on three curves: electronically routed paths, on–the–fly routed paths (optically bypassed), and overall paths. Only one WDM–PON EED curve is shown, because all packets were electronically routed in WDM–PON.

Figure 11 shows that the electronically routed paths of the enhanced t–λ routing architecture presented the lowest *EED* $\forall A$, because minor destination traffic (local traffic) perceived congestion free COs. The on–the–fly routed paths *EED* curve suggests that the ONUs passive buffers were overloaded for $A \geq 40\%$. In Figure 11 the enhanced t–λ overall EED curve indicates that when the passive buffers were overloaded ($A \geq 40\%$) there was an increasing portion of major traffic being lost, as is clearly showed in Figure 10.

The WDM–PON *LR* and *EED* curves depicted the WDM electronic bottleneck problem. Even though we have moved the bottleneck from COs to the ONUs in the enhanced t–λ architecture, producing a fast overload of the passive channels; the WDM–PON performance tends to worse when the network is highly loaded ($A \geq 70\%$). Figure 11 shows that the WDM–PON COs tend to get congested when the network load is increased. For $A \geq 70\%$ the WDM−PON *EED* becomes worse than the *EED* experienced by the enhanced t–λ architecture.

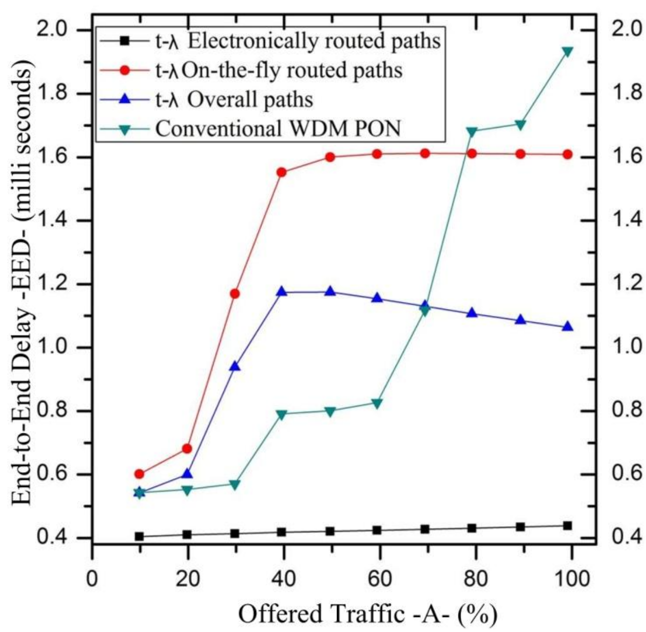

Figure 11. End–to–End Delay (*EED*) vs. Offered Traffic (*A*); for 70% of *A* destined to Metro Node (MN).

VIII. Conclusion and Future Work

In a future scenario with higher users' bandwidth demand for video–related traffic (video–related representing 61% of all customer traffic for 2015) and faster networks, the access network must successfully deliver the demanded bandwidth and cope with the strict traffic requirements on low delay and jitter.

A former t–λ routing architecture model feature was found, which produces constant packet reordering and performance problems. To avoid such packet reordering and performance problems, we have proposed an enhanced version of the t–λ routing architecture, which effectively avoids the reordering packet problems. The proposed scheme was evaluated against a traditional WDM–PON architecture using developed simulation models in the OPNET Modeler tool.

Although EED on WDM–PON and t–λ routing are not very different, our simulation results showed that the WDM–PON leads to congestion at COs in presence of nonuniform access traffic distribution, as a consequence of the electronic bottleneck. In spite of the fast overload of the passive channel at ONUs, the use of the proposed enhanced t– λ routing architecture, allows the COs to remain congestion free. In consequence, the introduction of optically bypassed channels leads to congestion avoidance, thus the network can more efficiently support different traffic requirements while reducing the power consumption.

In a future proof optical access scenario, each CO must manage much more than 64 ONUs. However, the t–λ routing architecture cannot meet this requirement because it presents a limitation in the number of ONUs managed by the CO.

The t–λ frame is composed by the same number of wavelengths as ONUs connected to the CO. Because of the time division multiplexing, in average each ONU experience a transmission rate $R_i = \frac{R}{N}\ bps$. The architecture was proposed to introduce the optical bypass of only one passive channel per CO [19]. In consequence, for each ONU the optical bypassed traffic experience in average a transmission rate of $R_i = \frac{R}{N}\ bps$, while the rest of the traffic experience in average a transmission rate of $(N-1)R_i bps$. Therefore, as the number of ONUs (N) increases, the average transmission rate of the passive channel perceived by each ONU decreases. In the case of a CO with 128 ONUs the average transmission rate of the passive channel perceived by each ONU will be $R_i = \frac{R}{128}\ bps$. In such scenario, the performance of the t–λ routing architecture will be very poor, because there will be one or just few channels associated with the major destination (up to 80% of offered load destined to major destination) increasing the bottleneck at the passive channel.

Hybrid Wavelength Division Multiplexing-Passive Optical Networks (XDM–WDM–PON) seems to be the solution to tackle the requirements for optical access networks of the future. The introduction of optical bypass (on–the–fly routed) channels based on the nonuniform access traffic distribution to achieve a transparent, low latency and low power consumption Metro–Access interface could represent an interesting useful approach to consider in XDM–WDM–PON architectures. Based on our simulation results, we propose to combine the best of the t–λ routing architecture and XDM–WDM–PON. A more effective combination could be by means of hybrid OFDM –WDM–PON or OCDM–WDM–PON, in substitution of the time division multiplexing. Such hybrid WDM–PON must be able to provide transparent ONU–CO connections and transparent Metro–Access optical bypass routed paths (releasing electronic bottleneck) without restrictions to increase the number of ONUs per CO.

It would be convenient to conduct some additional experiments introducing inelastic and elastic traffic differentiation. Using traffic differentiation can assure that only inelastic traffic will be sent by the optical bypassed channels, whereas elastic traffic could be sent through electronically routed channels.

ACKNOWLEDGMENT

This work has been supported by the Applied Networks and Telematics Group at Simon Bolivar University (GRETA–USB), Venezuela, and the Metro Access and Short Range Systems Group at Technical University of Denmark, Denmark.

REFERENCES

[1] R. Alvizu, M. Huerta, R. Gonzales, R. Martinez, L. Rodríguez, and I. Tafur, "On-the-Fly Routing and Traffic Self-Aggregation Towards Metro-Access Integration," in *INFOCOMP 2011, The First International Conference on Advanced Communications and Computation*, Barcelona, Spain, 2011.

[2] *Cisco Visual Networking Index: Forecast and Methodology, 2010-2015. http://www.cisco.com . 12.12.2011*.

[3] A. Di Giglio, *et al.*, "STRONGEST: Challenges for network architectures," in *Future Network and Mobile Summit, 2010*, 2010, pp. 1-8.

[4] J. i. Kani, "Enabling Technologies for Future Scalable and Flexible WDM-PON and WDM/TDM-PON Systems," IEEE J. Sel. Topics Quantum Electron., vol. 16, pp. 1290-1297, 2010.

[5] P. E. Green, "Fiber to the home: the next big broadband thing," IEEE Commun. Mag., vol. 42, pp. 100-106, 2004.

[6] L. G. Kazovsky, W.-T. Shaw, D. Gutierrez, N. Cheng, and S.-W. Wong, "Next-Generation Optical Access Networks," J. Lightw. Technol., vol. 25, pp. 3428-3442, 2007.

[7] X. Shilin, Z. Zhao, B. Meihua, Z. Min, and C. He, "Evolution scenarios for passive optical access networks," in *International Conference on Information Communications and Signal Processing (ICICS) 2011 8th*, 2011, pp. 1-5.

[8] E. Wong, "Next-Generation Broadband Access Networks and Technologies," J. Lightw. Technol., vol. 30, pp. 597-608, 2012.

[9] *Fiber-to-the-Home (FTTH) Council website. http://www.ftthcouncil.org/. 12.12.2012*.

[10] K. Prince, *et al.*, "GigaWaM−Next-Generation WDM-PON Enabling Gigabit Per-User Data Bandwidth," J. Lightw. Technol., vol. 30, pp. 1444-1454, 2012.

[11] K. Grobe and J. P. Elbers, "PON in adolescence: from TDMA to WDM-PON," IEEE Commun. Mag., vol. 46, pp. 26-34, 2008.

[12] C. Gee-Kung, *et al.*, "Key Technologies of WDM-PON for Future Converged Optical Broadband Access Networks [Invited]," IEEE J. Opt. Commun. Netw., vol. 1, pp. C35-C50, 2009.

[13] Z. Luying, C. Xiaofei, Y. Yong-Kee, and N. Lek heng, "Hybrid WDM-TDM PON architectures and DWBA algorithms," in *Communications and Networking in China (CHINACOM), 2010 5th International ICST Conference on*, 2010, pp. 1-6.

[14] P. Ossieur, et al., "A 135-km 8192-Split Carrier Distributed DWDM-TDMA PON With 2 x 32 x 10 Gb/s Capacity," J. Lightw. Technol., vol. 29, pp. 463-474, 2011.

[15] P. Ossieur, et al., "Demonstration of a 32 x 512 Split, 100 km Reach, 2x 32 x 10 Gb/s Hybrid DWDM-TDMA PON Using Tunable External Cavity Lasers in the ONUs," J. Lightw. Technol., vol. 29, pp. 3705-3718, 2011.

[16] N. Cvijetic, "OFDM for Next-Generation Optical Access Networks," J. Lightw. Technol., vol. 30, pp. 384-398, 2012.

[17] K. Fouli and M. Maier, "OCDMA and Optical Coding: Principles, Applications, and Challenges [Topics in Optical Communications]," IEEE Commun. Mag., vol. 45, pp. 27-34, 2007.

[18] J. i. Kani, *et al.*, "Next-generation PON-part I: Technology roadmap and general requirements," IEEE Commun. Mag., vol. 47, pp. 43-49, 2009.

[19] M. Wieckowski, A. V. Osadchiy, J. P. Turkiewicz, and I. T. Monroy, "Performance assessment of flexible time-wavelength routing for a self-aggregating transparent Metro-access interface," in *35th European Conference on Optical Communication (ECOC)* 2009, pp. 1-2.

[20] B. Mukherjee, *Optical WDM Networks*: Springer, 2006.

[21] *Metro Ethernet services - a technical overview.* http://metroethernetforum.org/PDF_Documents/metro-ethernet-services.pdf. *12.12.2012*.

[22] F. Davik, M. Yilmaz, S. Gjessing, and N. Uzun, "IEEE 802.17 resilient packet ring tutorial," IEEE Commun. Mag., vol. 42, pp. 112-118, 2004.

[23] P.-L. Tsai and C.-L. Lei, "Analysis and evaluation of a multiple gateway traffic-distribution scheme for gateway clusters," Comput. Commun., vol. 29, pp. 3170-3181, 2006.

[24] E. Van Breusegern, *et al.*, "Overspill routing in optical networks: a true hybrid optical network design," IEEE J. Sel. Areas Commun., vol. 24, pp. 13-25, 2006.

[25] A. V. Osadchiy, J. B. Jensen, P. Jeppesen, and I. T. Monroy, "Colorless receiver enabling crossconnect based metro-access interfacing nodes for optically labelled DQPSK payload signals," in *21st Annual Meeting of the IEEE Lasers and Electro-Optics Society (LEOS)*, 2008, pp. 612-613.

[26] S. Chatzi, J. A. Lazaro, J. Prat, and I. Tomkos, "A quantitative techno-economic comparison of current and next generation metro/access converged optical networks," in *36th European Conference and Exhibition on Optical Communication (ECOC)*, 2010, pp. 1-3.

[27] J. Berthold, A. A. M. Saleh, L. Blair, and J. M. Simmons, "Optical Networking: Past, Present, and Future," J. Lightw. Technol., vol. 26, pp. 1104-1118, 2008.

[28] C. Zhang, W. Zhao, and X. Yi, "100Gb/s technology and future development in China," in *OptoeElectronics and Communications Conference (OECC), 2011 16th*, 2011, pp. 169-171.

[29] E. Ip, *et al.*, "100G and Beyond Transmission Technologies for Evolving Optical Networks and Relevant Physical-Layer Issues," 100G and Beyond Transmission Technologies for Evolving Optical Networks and Relevant Physical-Layer Issues, vol. 100, pp. 1065-1078, 2012.

[30] R. Van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*: Artech House, 2000.

[31] N. Cvijetic, M.-F. Huang, E. Ip, Y.-K. Huang, D. Qian, and T. Wang, "1.2 Tb/s Symmetric WDM-OFDMA-PON over 90km Straight SSMF and 1:32 Passive Split with Digitally-Selective ONUs and Coherent Receiver OLT," in *Optical Fiber Communication Conference and Exposition (OFC/NFOEC), and the National Fiber Optic Engineers Conference* 2011, pp. 1-3.

[32] G. Wellbrock, "Preparing for the future," in *36th European Conference and Exhibition on Optical Communication (ECOC)*, 2010, pp. 1-10.

[33] A. Di Giglio, *et al.*, "STRONGEST: Challenges for network architectures," in *Future Network and Mobile Summit*, 2010, pp. 1-8.

[34] F. J. Effenberger, J. i. Kani, and Y. Maeda, "Standardization trends and prospective views on the next generation of broadband optical access systems," IEEE J. Sel. Areas Commun., vol. 28, pp. 773-780, 2010.

[35] S. Huan, K. Byoung-Whi, and B. Mukherjee, "Long-reach optical access networks: A survey of research challenges, demonstrations, and bandwidth assignment mechanisms," IEEE Communications Surveys & Tutorials, vol. 12, pp. 112-123, 2010.

[36] P. Chanclou, A. Cui, F. Geilhardt, H. Nakamura, and D. Nesset, "Network operator requirements for the next generation of optical access network," IEEE Netw., vol. 26, pp. 8-14, 2012.

[37] N. Cvijetic, et al., "1.92Tb/s coherent DWDM-OFDMA-PON with no high-speed ONU-side electronics over 100km SSMF and 1:64 passive split," Opt. Express, vol. 19, pp. 24540-24545, 2011..

[38] N. Cvijetic, et al., "Terabit Optical Access Networks Based on WDM-OFDMA-PON," J. Lightw. Technol., vol. 30, pp. 493-503, 2012.

[39] N. Kataoka, N. Wada, G. Cincotti, and K. Kitayama, "2.56 Tbps (40-Gbps x 8-wavelength x 4-OC x 2-POL) asynchronous WDM-OCDMA-PON using a multi-port encoder/decoder," in 37th European Conference and Exhibition on Optical Communication (ECOC), 2011, pp. 1-3.

[40] A. A. Ortega, V. A. Bettachini, J. I. Alvarez-Hamelin, and D. F. Grosz, "Point-to-point and Point-to-multipoint CDMA Access Network with Enhanced Security," 2011, p. ATuB6.

[41] F. Payoux, P. Chanclou, and N. Genay, "WDM-PON with colorless ONUs," in *Optical Fiber Communication and the National Fiber Optic Engineers Conference, 2007. OFC/NFOEC 2007. Conference on*, 2007, pp. 1-3.

[42] L. Ka-Cheong, V. O. K. Li, and Y. Daiqin, "An Overview of Packet Reordering in Transmission Control Protocol (TCP): Problems, Solutions, and Challenges," IEEE Trans. Parallel Distrib. Syst., vol. 18, pp. 522-535, 2007.

[43] *OPNET Technologies Inc.* http://www.opnet.com/. *12.12.2012*

[44] W. E. Leland, M. S. Taqqu, W. Willinger, and D. V. Wilson, "On the self-similar nature of Ethernet traffic (extended version)," IEEE/ACM Trans. Netw., vol. 2, pp. 1-15, 1994.

[45] B. Skubic, C. Jiajia, J. Ahmed, L. Wosinska, and B. Mukherjee, "A comparison of dynamic bandwidth allocation for EPON, GPON, and next-generation TDM PON," IEEE Commun. Mag, vol. 47, pp. S40-S48, 2009.