On-the-fly Routing and Traffic Self-Aggregation Towards Metro-Access Integration

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***Abstract* — The evolution and penetration of Optical Access Networks threatens to create a higher electronic bottleneck at Metro-Access interfaces caused by the ever increasing users' bandwidth demand. Since most of the newest applications are dominated by video-related traffic, there is a pressing need to relieve the electronic bottleneck between Access and Metropolitan area networks. In this work we present an enhanced version of time-wavelength access architecture with on-the-fly routing and traffic self-aggregation. The purpose of this architecture is to allow for a transparent Metro-Access integration with low latency and reduced power consumption. A WDM PON (Passive Optical Network with Wavelength Division Multiple Access) architecture was used as reference for comparison. The results obtained by the simulation model developed in OPNET Modeler show that the WDM PON will tend to produce electronic bottleneck issues, even though delays and loss rates are not very different in both architectures. These bottleneck issues can be avoided by the use of on-the-fly routing and traffic self-aggregation, which allows traffic to cope with the strict requirements of delay sensible applications. The proposed architecture is an interesting useful approach for Metro-Access integration and future access networks.**

Keywords- Future access network; on-the-fly Routing; Self-Aggregation; WDM PON; Metro-Access.

I. INTRODUCTION

The world is 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 [1]. Globally, Internet video traffic is expected to grow from 40% of all consumer Internet traffic in 2010 to a 61% in 2015.

To successfully deliver enough bandwidth to end users, the bottleneck at access networks must be avoided. Therefore, the introduction of optical fiber to the customer sites (FTTx; stands for fiber to the x, where x stands for Home, 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 [2][3].

The FTTH (Fiber To The Home) Council announces a continuous global growth of all fiber networks [4]. The average broadband access network speed grew 97% from 2009 to 2010 [1]. Most of this growth has been caused by deployments of PONs (Passive Optical Networks) based FTTx.

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 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 its point to multi-point nature, the 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 shared among all users the bandwidth available in a single wavelength. There are two main TDM PON standards used for mass rollouts [4][5]:

- 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 parts of 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 aggregated bandwidth, reach and power budget [5]. To solve these problems, it is widely accepted that the next evolution step for PON architectures is the introduction of wavelength division multiple access (WDM PON) [2][3][5]. The WDM PON approach assigns an individual wavelength to each ONU. This strategy allows the use of higher bandwidth for each ONU, a longer reach, better scalability towards higher users'

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concentration, and additionally provides transparent bit rate channels ONU-CO [3][5].

The continuous users' bandwidth demand growth is leading to 100 giga bits per second optical access systems [6]. This scenario implies that COs, supporting higher concentration of customers (with split ratio extended beyond 1:64), will have to aggregate and disaggregate traffic in volumes reaching tera bits per second. Thus, there will be a much higher congestion when managing the increasing bandwidth demand at the Metro-Access interface, and future applications' higher requirements on bandwidth guarantee and low delay application flow.

In this paper, we present an accurate performance assessment of an optical access network architecture that was originally proposed in [8]. This architecture introduces a time-wavelength (t-λ) routing for an on-the-fly (passively) routed, self-aggregating Metro-Access interface. The t-λ routing architecture, based on nonuniform traffic distribution in access networks, introduces lightpaths toward the most requested destinations, in order to relieve the electronic bottleneck and to simplify the Metro-Access interface.

Wieckowski et al. [8] have explained 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.

The 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 traffic's requirements. Therefore, the present work proves that the use of on-the-fly routing and traffic self aggregation is a very attractive approach for Metro-Access integration and future access networks.

The paper is organized as follows: Section 2 describes the Metro-Access interface problem and the t-λ routing optical access architecture. Section 3 presents related work on the t-λ routing architecture. Section 4 describes the simulation model developed and presents some simulation results. Section 5 describes concludes the paper.

II. METRO-ACCESS INTERFACE AND NETWORK ARCHITECTURE

The t-λ routing optical access architecture is based on the Metropolitan and Access networks traffic profile.

A. *Trafic profile of Metropolitan and Access Networks*

Typical carrier's network architectures have been deployed with one or at least a few interfacing nodes (gateways) between different network segments (Access-Metropolitan-Core). Therefore, there is more traffic that goes along different network segments through interfacing nodes (remote traffic) than traffic that goes along the same network segment nodes (local traffic) [7][9].

It has been observed that in a multiple gateway 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 [7]. This behavior can lead to insufficient capacity and can cause traffic bottlenecks at some points of the network.

General routing tasks rely on electronic processing, thus Optical-Electrical-Optical (O-E-O) conversions are needed. Each O-E-O conversion implies a number of complex operations (signal amplification, detection, error correction, buffering, frame searching, extraction from buffer, packet assembly and signal emission) resulting in high complexity and power and time consumption.

B. *Time-Wavelength (t-λ) Routing Optical Access network Architecture*

The t-λ routing optical access architecture exploits the traffic profile of access networks to introduce time-wavelength routing for a passive and self-aggregating Metro-Access interface [8]. The goal of the architecture is to use the nonuniform traffic distribution of access networks to select a portion of the traffic and forward it through passive channels to perform the on-the-fly routing (passive optical routing). By taking advantage of the reduced (electronic) processing achieved with on-the-fly routing, the electronic bottleneck can be relieved.

The selection of the traffic portion that will be routed on-the-fly relies on the analysis and evaluation of a multiple gateway traffic-distribution. In this distribution up to 70% of the traffic in the access networks is destined to a Metro-Access gateway (interfacing node), the so called major destination [7]. This implies that:

- Major destination traffic is sent through passive channels using on-the-fly routing at the COs.
- Minor destination traffic (local network 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 1). For the upstream channel the CO makes a time-wavelength assignment and sends a frame of interleaving Continuous Wave (CW) seed light to the ONUs.

Each ONU sorts packets at the customer sites on the basis of their destination. Colorless reflective modulators are used to transmit data by modulating the CW according to the predefined time-wavelength assignment [10].

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 (see Figure 1). Thus, each wavelength at the CO will contain data from several ONUs. The self aggregated traffic arrives at the CO, where passive channels are routed on-the-fly (based on the pre-defined wavelength assignment), while other packet traffic is sent to local processing units for destination inspection, routing and forwarding (electronically routed channels). As shown in Figure 1, the CO assigns $\lambda 1$ as passive channel. Hence $\lambda 1$ is self-aggregated and on-the-fly routed towards the major destination.

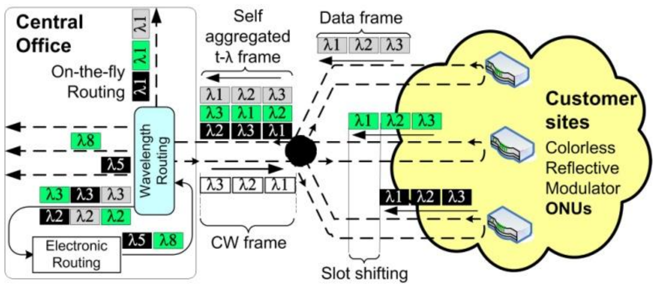

Figure 1. Underlying idea of the time-wavelength assignment and Central Office (CO) schematic diagram, for time-wavelength routed architecture to provide on-the-fly routing to Major destinations. CW: Continuous Wave.

III. Related Work

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) demand of future applications requirements. Thus, future-proof, cost and energy efficient Metro-Access interfaces have been extensively investigated [8][10][11].

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 [8].

Nevertheless 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 [8]. Furthermore, an improvement to the simulation model developed in the prior evaluation can be attempted because the excess traffic in passive channels (on-the-fly routed) originally was distributed to electronically routed channels.

The excess traffic in passive channels constitutes major traffic (traffic destined to a major destination) arriving at ONUs that produces overflows of buffers associated with the passive channels (passive buffers). Therefore, a portion of the major traffic goes through on-the-fly routed channels and, in the presence of overflows, another portion (the excess traffic) goes through electronically routed channels towards the major destination. This approach allows to use passive channels resources to the maximum and to distribute major excess traffic to 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 [8]. But users 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 Internet traffic in 2010 to 61% in 2015 [1]. Inelastic traffic applications especially video-related traffic has been flooding the networks, and future optical access networks must address the requirements of low delay and jitter.

The packets will arrive at major destination with high delay variations by distributing the excess traffic in passive channels through electronically routed channels. This behavior will lead to a 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 and video-related traffic): The packet reordering compensation adds additional delay. Thus, inelastic traffic will be most likely to be discarded because, even when reaching the destination, it will not fulfill 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's 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's overload [12].

IV. Performance Assesment

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, an event-based state-of-the-art network modeling and simulation tool [13].

A. Simulation Model

The simulation models are composed of ONU nodes and CO nodes, which are connected by point-to-point links with several channels (i.e., wavelengths). There is also a Paths Computation Entity node used to create the routing tables of the nodes and establish the on-the-fly routed paths, based on a variation of the Dijkstra algorithm using the DJK OPNET Modeler packet [13]. The Metro-Access Interfacing Node is a CO node with different attributes configuration.

Each ONU connected to a CO has a dedicated wavelength in the WDM PON models. All the wavelengths are terminated at COs to apply electronic routing.

The t-λ frame in the t-λ routing architecture is composed by the same number of wavelengths as ONUs managed by the CO. Thus each ONU time shares the same number of wavelengths as there are ONUs connected to the same CO. The CO establishes on-the-fly routed paths from each ONU towards the major destination. Hence, those wavelengths associated with the major destination are passively routed at the COs.

The models built in the event-based simulation tool OPNET Modeler enable a more accurate evaluation. The main performance metrics of the model are:

- Traffic Loss Rate (*LR*): relation between bits loss and bits sent by the ONUs.
- End-to-End Delay (*EED*): time difference between the time instant when a packet's first bit arrives at

ONU and the time instant when the packet´s last bit is received at destination.

The Offered Load has been used to assess the architecture under various loads. This translates into different degrees of congestion.

It is well known that Internet traffic presents self-similar behavior. Thus the ONU nodes generate the network traffic with self-similar arrivals processes, using a variation of the OPNET raw packet generator [13].

Because the t-λ routing architecture has been proposed as a solution for a transparent and self aggregating Metro-Access integration, it must consider that inelastic traffic will flood future networks. Therefore, in the developed t-λ routing architecture model (enhanced version) the excess traffic in passive channels is dropped at the ONUs. Thus the delay variations and the packet reordering problems are avoided (see Section 3).

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 for major traffic from the COs to the ONUs). The fact is that, if some packets should be discarded by a network bottleneck, it is better that this happens as soon as possible. And this is precisely what the proposed enhanced t-λ routing architecture does.

B. Performance Assessment Escenario

Figure 2 presents the simple network topology used in the simulation experiments. The topology was selected in order to get the possibility to establish some comparison with the former evaluation [8]. It consists of five COs with four ONUs connect 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 is connected to the MN.

The performance assessment scenario's set up was as follows. Transmission Rate R = 125 mega bits per second (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 milli seconds in relation with the transmission rate; based on design considerations assumed in [14].

The applied traffic model has self-similar arrivals processes with Hurst parameter $H \sim 0{,}74$; based on empirical traffic evaluations [15]. The traffic distribution was the same as used in the former evaluation and was taken from a multiple gateway traffic assessment, where 70% of the offered load (A) is destined to the major destination (i.e., the MN) and the rest is equally distributed among the minor destinations (i.e., the five COs)[7][8].

The t-λ frame period was set to 125 micro seconds in the t-λ routing architecture; compatible with the Synchronous Digital Hierarchy (SDH).

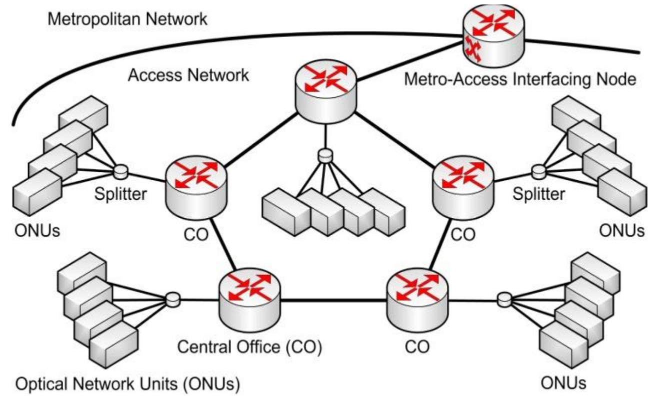

Figure 2. Simple Access network topology used for the performance evaluation, based on a ring interconection of COs. The Metro-Access interfacing Node (MN) represents the major destination (for the performance assessment up to 70% of traffic was destined to MN).

Each frame is composed of four t-λ slots (same number as ONUs connected to each CO), which were assigned in such a way that wavelengths were associated with the MN as the major destination and the COs as minor destinations.

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

C. Simulation Results and analysis

Performance assessment was carried out using a worst case electronic bottleneck scenario; i.e., up to 70% of the offered load (A) is destined to the major destination (MN). As there are four ONUs per each CO (see Figure 2), the t-λ frame is composed of four time shared wavelengths. Only one wavelength is passively routed towards major destination per each CO (i.e., one on-the-fly routed path established from CO to MN). In this way each ONU perceives up to 25% of the transmission rate to send traffic into the passive channel, producing fast overload of the passive channels.

Figure 3 shows the simulation results for *LR* (Loss Rate) and *EED* (End-to-End Delay) vs. *A* (Offered Load) for the enhanced t-λ routing architecture and the conventional WDM PON as reference. As can be observed in Figure 3(a), 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 worsen when *A* increases (higher degree of congestion in the network) as a consequence of the COs' electronic bottleneck.

Figure 3(b) presents the *EED* experienced by the enhanced t-λ routing architecture, as based on three curves: electronically routed paths, on-the-fly routed paths, and overall paths. Only one WDM PON *EED* curve is shown, because all packets are electronically routed in WDM PON.

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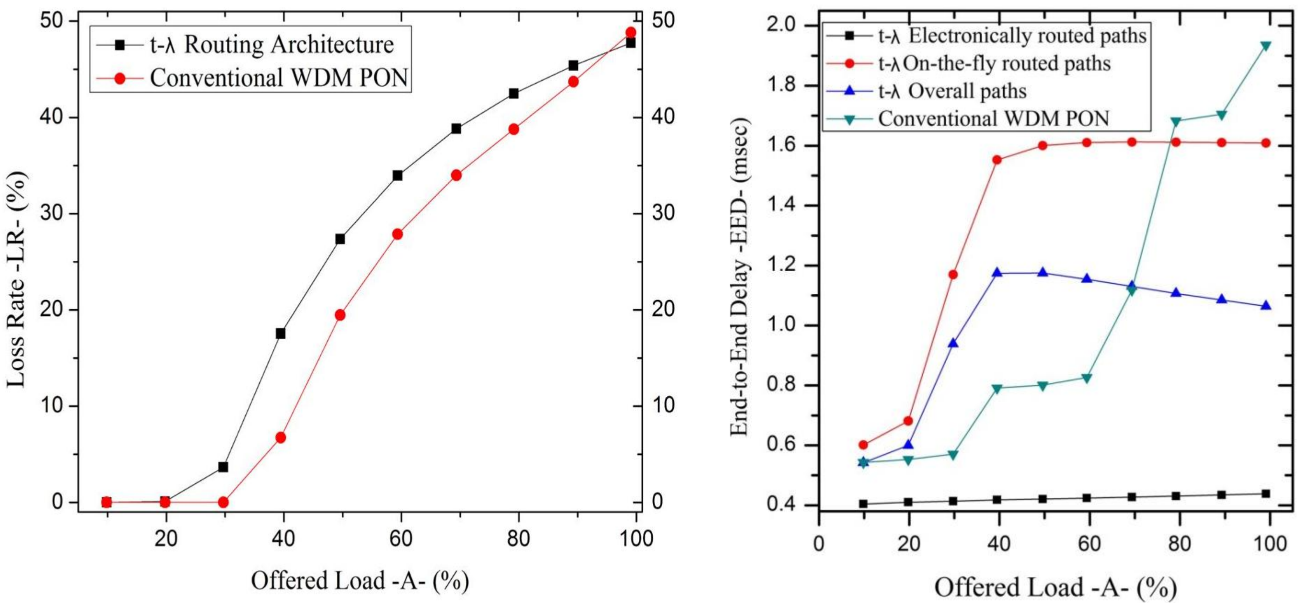

(a) (b)

Figure 3. Simulations Results for 70% of *A* (Offered Load) destined to Metro Node (MN).

(a) Loss Rate (*LR*) vs Offered Load (*A*); (b) End-to-End Delay (*EED*) vs. *A*

Figure 3(b) shows that the electronically routed paths of enhanced t-λ routing architecture presents the lowest *EED* ∀ *A*, because minor destination traffic (local traffic) perceives 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 3(b) the enhanced t-λ overall *EED* curve indicates that when the passive buffers were overloaded ($A \geq 40\%$) there is an increasing portion of major traffic that is lost, as is clearly showed in Figure 3(a).

The WDM PON *LR* and *EED* curves depict 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 be worse when the network is highly loaded ($A \geq 70\%$). Figure 3(b) shows that by using WDM PON the 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.

V. CONCLUSION AND FUTURE WORK

In a future scenario with higher users' bandwidth demand for video-related traffic (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 deal with this issue 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 the OPNET Modeler tool.

Even though 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 passive channel's fast overload at ONUs, the use of the proposed enhanced t-λ routing architecture, allows the COs to remain congestion free, there is reduction of the network´s power consumption and the network can more efficiently support different traffic requirements.

The introduction of on-the-fly routed passive channels based on the nonuniform access traffic distribution could represent an interesting useful solution for transparent and low latency Metro-Access integration.

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 passively routed channels, whereas elastic traffic could be sent toward electronically routed channels.

In a Metro-Access integration scenario each CO must manage much more than 64 ONUs. However the t-λ routing architecture presents a limitation in the number of wavelengths that each ONU will manage (the t-λ frame is composed of the same number of wavelengths as ONUs managed by the CO). In consequence, the scalability on the number of ONUs managed by each CO is limited.

Based on our simulation results, we propose to combine WDM PON with the use of on-the fly routing and self aggregation for traffic going toward the major destination (i.e., Metro-Access Interface). This combination is possible by means of hybrid WDM with Sub Carrier Multiple Access (SCMA) or with Optical Code Division Multiple Access

(OCDMA). Such a combination would provide transparent ONU-CO connections and transparent Metro-Access on-the-fly routed paths (releasing electronic bottleneck) without restrictions to increase the number of ONUs per CO.

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