Building Efficient End-to-End Service Transparent Fiber Networks Supporting Access Rates Beyond 10Gb/s

Theofanis G. Orphanoudakis, Chris Matrakidis, Christina (Tanya) Politi, Alexandros Stavdas
Dept. of Informatics and Telecommunications
University of Peloponnese
Tripolis, Greece
{fanis, cmatraki, tpoliti, astavdas}@uop.gr

Helen-Catherine Leligou, Evangelos Kosmatos
Dept. of Electrical Engineering
Technological Educational Institute of Central Greece
Psahna—Evia, Greece
leligou@teihal.gr

Abstract— **Currently, networks are developed based on the layered model focusing on customized solutions for the access, metro and core domains. Access networks rely upon centralized packet multiplexers, while core network switches rely on large port count electronic switches assisted where appropriate by Optical Cross-Connects (OXCs). However, this monolithic model can lead to capacity and space bottlenecks, compromise network services because of a lack of common feature sets, and limit the revenue that data services can produce for operators. In this paper, we present a novel control plane solution, which can lead to metro network segment collapse and access-core integration supported by an efficient traffic control and distributed multiplexing scheme based on a hybrid long-reach fiber access network architecture. We show that this architecture can be exploited as a large scale distributed multiplexer that can be used to funnel traffic directly from access networks over a core optical network and describe a control plane architecture compatible with the concept of Software Defined Networking for simplifying the aggregation process and improving performance at the same time.**

Keywords-Passive optical networks; wavelength division multiplexing; access-core integration; medium access control; FTTx.

I. INTRODUCTION

Telecommunications traffic is soaring at an astonishing rate. Worldwide, the average traffic will increase threefold over the next five years [15]. The evidence we have so far indicates that the demand for even higher capacity networks is steadily increasing. The widespread availability of bandwidth intensive services and advanced Fiber to the x point (FTTx) schemes will have dramatic consequences in core networks: In this paper, we propose a network control and data plane architecture aiming to capitalize on the complementary strengths of “optical” and “electronics” technologies so as to design an ultra high capacity end-to-end network solution allowing for transparent core-access integration. The existing and new services/applications that are becoming available to the end user are currently supported by wireline access technologies, such as relatively limited capacity cable modems, and Digital Subscriber Line (DSL) [14] or high capacity FTTx/Very-high-bit-rate DSL (VDSL) [13] as well as wireless technologies such as mobile 3G/4G/Long Term Evolution Advanced (LTE-A) networks (High-Speed Downlink Packet Access (HSDPA)/High Speed Packet Access (HSPA)+) [12], WiFi and WiMax. Wireless networks feature high flexibility in terms of broad area coverage but face the limitations of relatively low bandwidth (10’s to a few 100’s of Mbps shared between all the users in a cell). Therefore, next generation fiber access networks are ultimately expected to become a universal access networking platform for broadband service delivery either directly to end-users or as a wireless/mobile access backhaul infrastructure.

While deployment of dedicated fibers per subscriber may prove economically unjustifiable, there are several solutions that may lead to resource sharing, hence, cost reduction. Passive Optical Networks (PONs) were initially proposed in 1980s to efficiently concentrate/distribute traffic via a commonly shared, passive tree-shaped topology. Under this scheme, the time sharing of this topology allowed traffic from multiple Optical Network Units (ONUs) to reach, collision free, a single port at the Optical Line Termination (OLT) [1]-[3].

In the core network, L2/L3 switches and routers are progressively pushed back to core network periphery. Thanks to architectural changes in access networks a trend for significant core node consolidation is emerging i.e., fewer, but higher capacity, nodes across the network. Hence, efficient ways to aggregate and transport traffic over the core network infrastructure are required. The objective is to exploit the immense capacity offered by optical transportation systems, while avoiding the cost of electronic switching at transit nodes. This task in turn requires appropriate traffic grooming and forwarding schemes that can operate at the optical layer and reduce conversions to the electronic layer as much as possible to reduce costs. In order to achieve this, a coordinated end-to-end network operation is required. This coordination must take into account the boundaries of different administrative domains and provide appropriate interfaces to allow exchange of information and implementation of a distributed information forwarding and traffic aggregation scheme.

In the rest of this paper, we describe the framework for developing such a network architecture. In the following section, we focus on the end-to-end network view and the

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core network functionality. In Section III, we describe an interoperable long reach access network architecture that can lead to access-core integration. In Section IV, we describe an integrated resource reservation scheme that can operate over both Wavelength-Division Multiplexing (WDM) and Time-Division Multiplexing (TDM) shared optical networks. In Section V, we evaluate the proposed scheme under specific scenarios. Finally, Section VI concludes our paper.

II. END-TO-END NETWORK ARCHITECTURE

The objective of an end-to-end network is to collect the traffic from the access part and forward it to the recipient access network while providing the requested Quality of Service (QoS) performance. Our approach is to optimize the performance in this segment proposing suitable network and node architectures in the framework of dynamic networking while ensuring backwards compatibility. The overall vision is shown in Figure 1. The main ideas are to remove the need for a physical aggregation network, use optical interconnection between access and core whenever possible, and still reap the benefits of statistical multiplexing to achieve efficient use of resources, i.e., exploiting access-core integration [4].

In order to achieve the objective of efficiency (i.e., reduced deployment and operational costs), the network must implement efficient traffic aggregation and routing schemes so that the available fibers and switch ports are utilized to the greatest possible extent. Additionally, the transparency at the optical layer should be maintained to the greatest possible extent as well, so as to reduce the increased cost of deploying complex and costly in terms of power consumption packet routers. Transparency could be achieved in different forms. Ultimately, optical transparency could guarantee traffic forwarding directly at the optical layer. In this case scalable optical switches could be exploited. However, this is difficult to achieve since traffic flows need to be redirected based on flexible rules that lead to specific requirements about traffic processing at each node. While optical transparency is difficult to achieve end-to-end in long paths, we will show that the same objectives can be achieved if service transparency is maintained. By service transparency, we refer to aggregation and processing of traffic flows aggregated and managed in terms of provisioned network services that can lead to reduced complexity and efficient implementations. Thus, core optical nodes can be exploited for transportation and switching of large traffic containers at extremely high data rates. Network and node architectures to achieve these objectives has been described in [5][6].

This could exploit a flexible and scalable control plane to allow exchange of information across domains so as to achieve implementation of optimal traffic aggregation rules so that well utilized optical flows are switched end-to-end across network segments remaining entirely in the optical domain. In the example of Figure 1, under appropriate coordination of reservations in the access domain (1) of the source node traffic from different user interfaces and services can be aggregated and transported over appropriately formed L2 traffic containers. Such containers can then reserve wavelength resources (possibly time-shared) over the core domain (2, 3 in Figure 1) and reach the recipient over appropriately reserved resources at the destination access domain (1’ in Figure 1).

To achieve optimal resource utilization in the network,

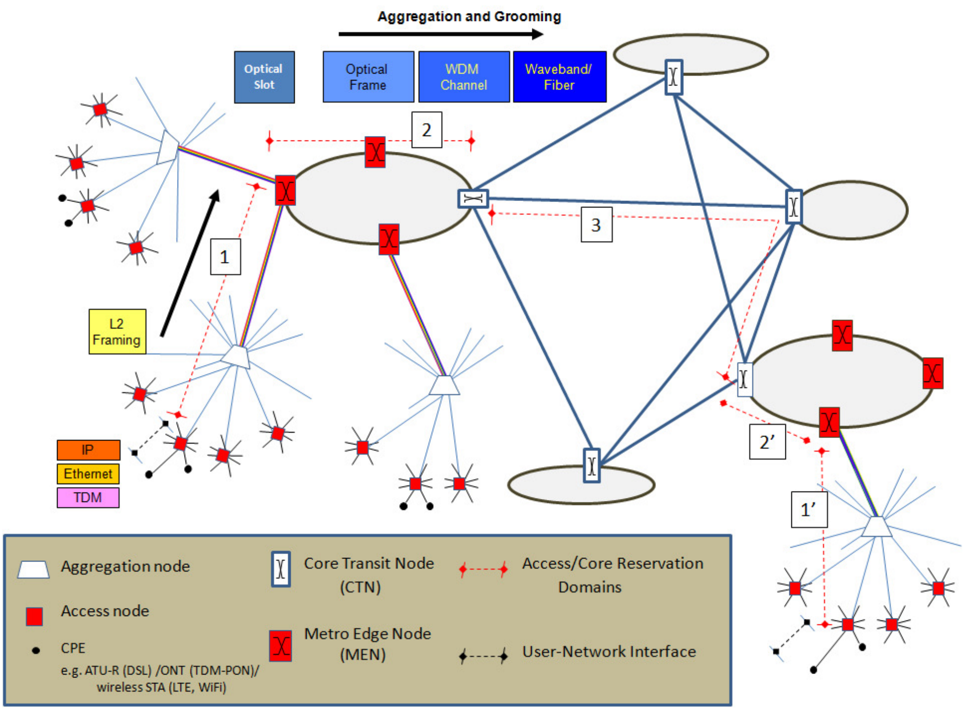

Figure 1. End-to-end network architecture and resource reservation domains.

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however, the end-to-end paths signaled by the network control plane must be computed based on available network status information at each segment. Taking into account the requirement for interoperability across administrative domains this can be addressed through the introduction of an appropriate path computation architecture, where peering or hierarchical Path Computation Elements (PCEs) will cooperate for the computations of end-to-end optimal paths, even in scenarios spanning different administrative domains (Figure 2). Such a distribution of the path computation functionality network serves a two-fold purpose. First, by deploying a PCE per network segment (e.g., one per cluster and another in the core part connecting CTNs), a scalable path computation tailored to the characteristics of each network segment can be implemented. Furthermore, assuming that network segments are owned by different network operators, optimal end-to-end path computations without compromising the confidentiality between domains can still be achieved. For instance, this would likely be achieved through the deployment of hierarchical PCE architectures, or the usage of path-key mechanisms amongst peering PCEs.

The above scheme suggests a seamless integration of abstraction and resource orchestration mechanisms across the entire physical layer infrastructure. Towards this end, new technologies for optimal configuration and planning to reduce costs, simplify management, improve service provisioning time, and improve resource utilization in multi-domain networks become increasingly important. Ideally, an application or service could be completely decoupled from the underlying network infrastructure, but this is not always realistic. In most cases, access to the specific underlying infrastructure quality performance indicator factors and resource management mechanisms, is required in order to establish and manage specific Service Level Agreements (SLAs). To meet application performance objectives, it becomes necessary for the application or its proxy to ensure that the underlying network is aware of the application requirements and provides the necessary services. This is a task of the network control and management plane entities in order to appropriately map applications to offered services configure the network elements and orchestrate reservation of resources across network segments. While proprietary implementations exist to achieve the interactions described above most are based on some sort of a network control plane that utilizes specific interfaces and protocols. The objective is to decouple network processing and information forwarding data plane functions from the service composition, configuration and management functions. To support transport networks with multiple administrative and technology segments, communication and interoperability between control planes is required. The mediation between control and transportation, layers can facilitate joint optimization of computing and networking deployments, software-defined functions at a number of layers, including the transport (i.e., optical and TDM) layer, enabling simpler interworking of different administrative and technology domains, and application-aware transport network resources.

Motivated by the above objectives and in order to replace proprietary implementations and manual processes with an automated control plane mechanism the Software Defined Networking (SDN) paradigm has emerged [7][8]. The recently introduced SDN concept based on the OpenFlow [8] protocol relies on a complex notion of a flow associated to a number of header fields in the data frame, which enables the definition of detailed rules for the treatment of different traffic classes and owners. Because of this, SDN is seen as a potential solution for a unified control plane in converged access/aggregation and mobile networks. Thus,

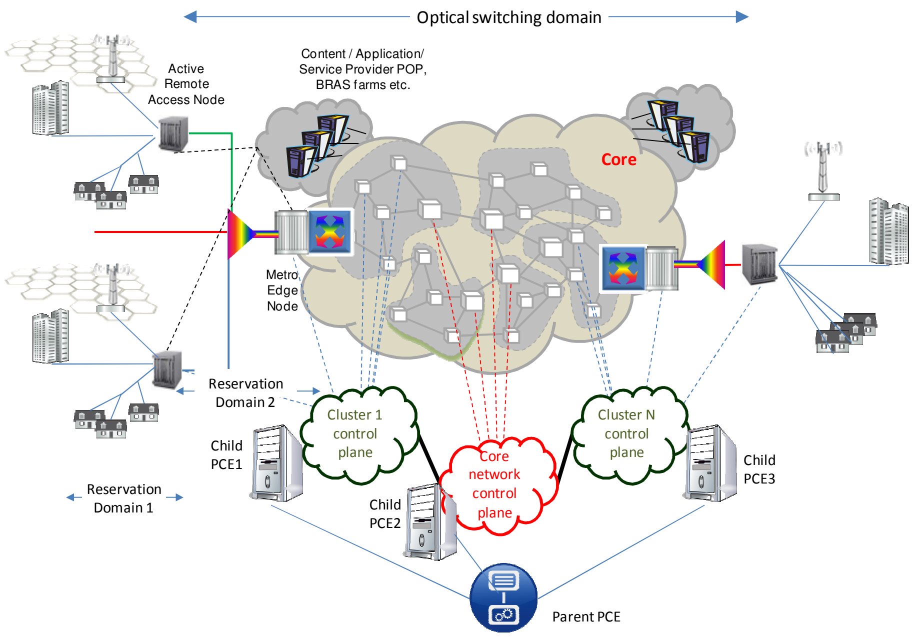

Figure 2. SDN based control plane, hierarchical scenario.

SDN principles could be employed to implement service delivery policies and coordinate end-to-end reservations implementing the framework described above resulting in efficient service transparent optical networks.

III. Access Network Architecture

Having described the vision for achieving service transparency over the core network, we should also focus on how to achieve deeper fiber penetration in the last mile building an end-to-end optical infrastructure maintaining service transparency so as to increase efficiency and reduce complexity. Towards this end, we first describe the available technologies and architectural components that can be used to develop dynamic optical access networks and present a scalable reference access network architecture. In the following section, we will describe how the control plane mechanisms described above can be extended to support end-to-end resource reservation schemes across the entire optical network.

WDM-PONs, possibly complemented by TDMA techniques, are considered the next step in the evolution of PONs. They can lead to higher per-ONU bandwidths, splitting ratios, and reach, as compared to EPON and GPON architectures due to the higher capacity per fiber. The use of WDM-PONs enables new broadband business and residential applications on a broad scale, and enables the evolution of metro area networks towards a unified access and backhaul infrastructure. Different per-wavelength bit rates ranging from 1 to 10 Gb/s have to be supported, and full integration into a management system and also into a control plane is necessary.

A WDM-PON architecture mainly depends on the use of the so-called Remote Nodes (RNs), which are used as wavelength (de)multiplexing points and the design of ONUs (Figure 3a). In WDM-PONs as a basic multiplexing stage most frequently, a wavelength routing device (like an Arrayed Waveguide AWG, used in a single or in multiple stages) or wavelength filters with specific properties also including power couplers are used. To achieve higher flexibility next-generation WDM-PONs should have the capabilities of flexible wavelength routing to sub-trees and in turn provide some sort of wavelength agility in the ONU side. Different degrees of flexibility in wavelength routing could be provided by supporting sharing of wavelength across different sub-trees. The latter option assumes some sort of wavelength agility on the ONU side to operate in different wavelengths.

In [9][10], an efficient long-reach access network supporting the above features based on the introduction of the Active Remote Node (ARN) in the access network exploiting a Fibre-to-the-Curb (FTTC) architecture has been presented. The ARN is physically sited close to the end-user, e.g., where the Cabinet/DSLAM is located and its role is to terminate and (de)aggregate the traffic from/to a group of end-user ONUs in the same neighbourhood (Figure 3b). Thus, the ARN is the place where optical transparency is terminated creating a two-stage optical access network.

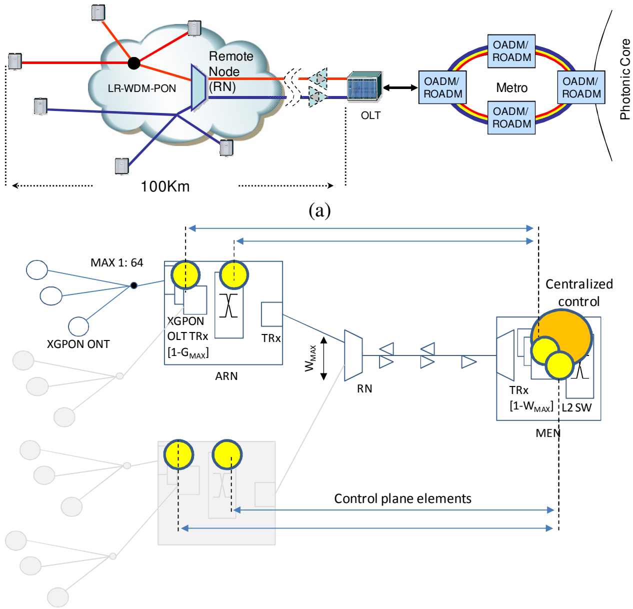

Figure 3. Generic WDM-PON architecture (a) and two-stage hybrid TDM/WDM PON

This architecture has been shown to reduce cost and increase scalability [10]. The most important features of the two-stage hybrid TDM/WDM PON of Figure 3b is that access rates beyond 10Gb/s per user can be achieved using cost efficient ONUs (e.g., XGPON [2]) while increasing aggregate capacities over the WDM trunk line.

Concluding, we summarize below the main points of the architecture described above. First, the flat hierarchy exploits optical transmission and multiplexing to a minimize the cost of packet processing and switching, since long-reach can be achieved (as proposed in [4][6]). The second contribution of this paper is that an integrated control plane architecture is proposed to implement this network hierarchy. Beyond simplification of the access routers and switches the proposed architecture can also lead to reduction of cost and power consumption due to the simplification of the Customer Premises Equipment (CPE), while maintaining very high access rates that can exploit mature 10Gb/s technologies. Below, we will finally show that the proposed integrated optical network architecture can exploit service transparency to also further reduce the implementation cost of multiple access control and access latency over the shared network paths of tree-shaped access networks.

IV. Integrated Resource Reservation Scheme

The access architecture described above evidently defines two discrete resource reservation domains extending between the active nodes of the network (i.e., the customer ONUs, ARN and MEN), as depicted in Figure 2 and Figure 3b. Assuming TDM-PONs in the last drop from the ARN to the customer ONUs resource reservation in the first segment would be performed following the Medium Access Control (MAC) protocol and the associated traffic management mechanisms [1]-[3]. In both IEEE 802.3 based Ethernet PONs (EPONs) and the ITU based G-PONs this assumes the implementation of a number of discrete Classes of Service (CoS) and the corresponding per CoS queuing and request process in the ONUs and MAC scheduling of timeslot allocations per ONU and CoS (transmission grants) at the OLT [11]. If the two segments operate independently, forwarding of traffic aggregated by each OLT over the core network would then typically require routing/switching of traffic to output interfaces. Implementing appropriate output queuing policies CoS scheduling would handle the transmission over each output interface. This is schematically shown in Figure 4a, where M input (access) interfaces (OLTs) aggregating traffic from PONs with a split ratio N are interconnected to L core network destination nodes (Di) over K output (core) interfaces.

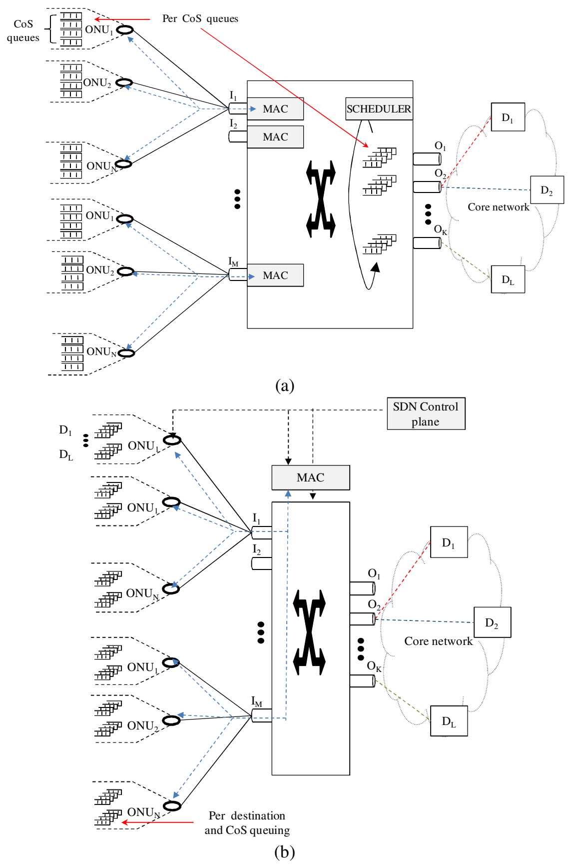

Figure 4. Distributed per segment queuing and scheduling (a) vs. SDN controlled distributed multiplexing and centralized MAC (b)

Implementing the SDN approach described in Section II, flexible flow association rules can be defined (e.g., using the OpenFlow protocol) across the entire optical access and core network up to the ONUs. This can make possible an alternative queuing and reservation policy (following the approach of [11]), which can handle collectively upstream requests and perform scheduling and traffic forwarding in a centralized manner, as shown in Figure 4b.

In this paper, we extend the work presented by Orphanoudakis et al. [11] to address hybrid WDM/TDM networks as proposed by Matrakidis et al. [9] assuming an SDN compatible mode of operation estabishing provisioned links over the core network to implement flow forwarding based on programmable rules. Thus, even packet switching at the ARN side can be simplified by appropriate frame tagging techniques like VLANs or MPLS. Finally, the centralized arbitration eliminates the requirement for buffering at the output interfaces.

It is worth noting that this scheme does not increase the complexity of ONUs, since per flow queuing is already implemented and only the number of queues is increased (not affecting the total memory requirements though, as will be shown next) to implement per destination queuing as determined by SDN rules. On the contrary, a single MAC entity can be used to collectively schedule upstream transmissions from all access networks so as to optimally utilize connections over the core network eliminating the need for output queues and scheduling. Thus, the network will operate as a distributed switch under the control of the centralized MAC arbiter. Since the single MAC entity has global knowledge of traffic conditions at each ONU as well as the status and service rate of each core interface we will show that improved access latency as well as throughput can be achieved.

V. PERFORMANCE EVALUATION

In order to evaluate the performance of the proposed scheme, a simulation model implementing the two-stage hybrid TDM/WDM PON shown in Figure 3b was developed using the OPNET simulation tool. The simulated topology comprises 4 PONs, with 16 ONUs each, the capacity of each PON being set to 10Gb/s. We consider two traffic classes (high priority and low priority class). The traffic arrival pattern of the high priority class were simulated by constant bit rate sources generating short fixed-size packets periodically. This service class is expected to serve mostly traffic from real-time services with high QoS requirements. The traffic arrival pattern of the low priority class were simulated by ON-OFF sources (modelling self-similar Internet traffic) with a burstiness factor of 8. Regarding the packet size, the tri-modal distribution was used as is proved to be good approximation of IP applications originating in Ethernet networks. In detail, it consists of packet sizes of 64, 500, 1500 bytes appearing with probability of 0.6, 0.2, and 0.2 respectively. The traffic mix included on average 30% high priority traffic and 70% low priority traffic. The number of destination core nodes (L) was set to 13. In order to simulate an unbalanced traffic demand per destination all packets from the first ONU in each PON, were set to have as destination a single core node, while for the traffic from all the other ONUs its destination was randomly selected by using a uniform distribution among all destinations.

Following the methodology of [11], we compared this architecture with a non-integrated one, where the OLT MAC schedules the transmission of each PON independently. In this architecture the OLT decides on scheduling by taking into account only the requirement for fair sharing of resources among all competing ONUs (denoted hereafter as “Distributed” MAC implementation referring to Figure 4a).

Figure 5 illustrates the probability density function (PDF) of access delay (across all queues of all ONUs) for a total offered load of 95%. Evidently, the proposed centralized architecture achieves lower aggregate access delay at high loads (at low loads demands per output interface remain low; hence, there is no impact of the MAC scheduling).

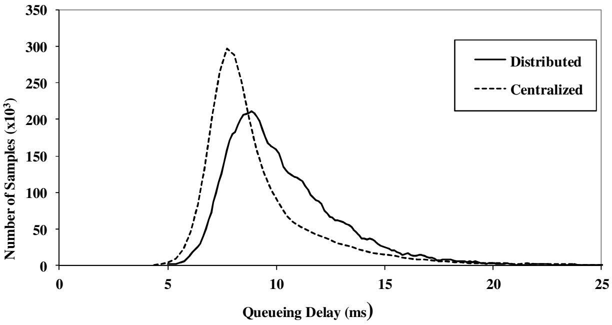

Figure 5. Probability Density Function (PDF) of access delay at 95% load.

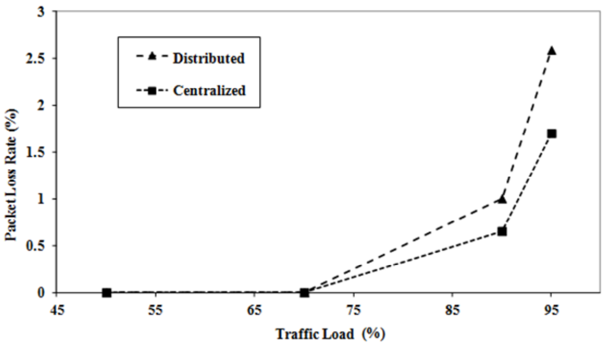

Figure 6. Packet Loss Rate (PLR due to buffer overflows.

The improved access latency of the centralized MAC we propose in this paper, also has an impact on the total buffering requirements as observed in Figure 6, where the packet loss probability in ONU queues is shown. As can be deduced by observing the results in Figure 6, the distributed MAC results in higher losses and reduced throughput for an ONU buffer size value of 16Mbits, while for the centralized MAC proposed here this value is up to 30% improved.

VI. CONCLUSIONS

We described an end-to-end optical network architecture that can efficiently scale to support the requirements of next generation networks. The proposed architecture exploits flexible core networks based on efficient traffic aggregation and optical switching and integrated access-core networks based on hierarchical long reach hybrid TDM/WDM PONs allowing access rates beyond 10Gb/s. Based on this network architecture, we proposed a unified control plane architecture that can perform end-to-end coordination and resource reservation based on SDN principles. Hence, ultra high capacity service transparent optical networks can be deployed exploiting the emerging SDN principles to implement traffic aggregation and flow switching. A scenario of operation of this integrated resource reservation scheme and centralized control was assessed by means of simulation and was shown to achieve improved performance in terms of throughput and access latency. Additionally, the proposed scheme can lead to lower complexity of the access nodes since a centralized MAC engine guided by an SDN control plane can replace multiple engines that would be needed in the case of distributed control.

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