Future Internet infrastructure based on the transparent integration of access and core optical transport networks

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It is increasingly recognized that the Internet is transforming into a platform providing services beyond today's expectations. To successfully realize this transformation the structural limitations of current networking architectures must be raised so that information transport infrastructure gracefully evolves to address transparent core-access integration, optical flow/packet transport and end-to-end service delivery capability, overcoming the limitations of segmentation between access, metro and core networks and domains. In this paper we propose and evaluate an integrated control plane for optical access and core networks, which addresses the above consideration. The proposed control plane can lead to a unified transport infrastructure integrating state-of-the-art components and technologies including Wavelength Division Multiplexing, Passive Optical Networking and Optical Packet Routers with inherent traffic grooming capabilities. The performance of the proposed architecture is assessed my means of simulation in terms of cost, resource utilization and delay.

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1. Introduction

Future Internet is expected to provide a data-centric networking platform providing services beyond today's expectations for shared workspaces, distributed data storage, cloud and grid-computing, broadcasting and multi-party real-time media-rich communications and many types of e-services such as sophisticated machine-machine interaction between robots, e-health, and interactive e-learning. These evolving services are expected to introduce a major leap in the networking infrastructure, which will be developed and maintained by new types of operators that shall collaborate to provide connectivity, Internetworking and content delivery services [1]. This mandates that access and backbone networks become progressively dynamic with respect to the transported traffic volume, to the spatial and temporal variations of traffic's patterns and to the subsequent interconnection request patterns. Following these evolutionary steps the legacy model and definition of access, metropolitan and core networks will not suffice to define next-generation ultra-high capacity transport network architectures, which will be dominated by the steadily increasing expansion of optical networking infrastructures towards the end-users premises. In this work we present an optical transport network architecture that addresses these new requirements and can result in an integrated and interoperable system design with reduced complexity and enhanced performance.

Before we proceed in the description and evaluation of the proposed traffic aggregation, switching and network control schemes we review in the following section the motivations and trends that are expected to introduce new technologies and affect the hierarchical organization of the transport network infrastructure. In Section 3 we review the existing state-of-the-art and technologies and architectures that have been recently investigated in the literature and emphasize on the application of WDM technology over Passive Optical Networks as a viable technology for next-generation optical access and dynamically switched optical core networks. In Section 4 we present an alternative architecture for optical core-access network integration and discuss the details of the proposed network control plane design, resource allocation and scheduling schemes. In Section 5 we present performance evaluation results comparing the proposed integrated architecture with non-integrated WDM-PON optical access and burst switched optical core networks. Finally in Section 6 we conclude our paper and summarize the next steps for evaluating alternative implementations of the proposed architecture and their potential impact on end-to-end performance under different optical switching techniques and switching node technologies.

2. Current trends in optical transport networks

In order to elaborate on architectures for integrated data transport over multiple segments of an optical network infrastructure we discuss in this section the basic trends that are expected to affect the evolution and possibly re-define current definitions of network segments classifying networks into local, access, metro and core domains and respective nodes to types of equipment like customer premises equipment, access, edge and core nodes.

With respect to what is currently defined as a backbone (either core or metro) network infrastructure in the quest for higher reliability and lower OPEX, the trend is to migrate from manual/labor intensive OA&M functions towards full automation. To accomplish this task, the deployment of advanced techniques like dynamic multi-layer control plane, traffic engineering etc aiming to render a network adaptable and reconfigurable at will, is mandatory. In parallel, the aforementioned applications have dissimilar bandwidth and end-to-end QoS requirements leading to spatial and temporal variations in the traffic patterns across a network domain. To cost-effectively accommodate these variations, statistical multiplexing of the network resources i.e. sharing the common resources in a controlled manner, is mandatory. Static multiplexing techniques based on legacy CWDM/DWDM metro rings and OADM or even dynamically reconfigurable ROADM nodes are reaching their limits and have sparked today a renewed interest for Optical Packet Routers (OPRs).

With respect to what is currently defined as an access network segment the main evolutionary changes are expected to be introduced by the steadily increasing demand for even higher capacity networks. Telecommunication carriers worldwide are realizing that their aging copper access infrastructure is being taxed as residential and business customers utilize ever-increasing, symmetrical bandwidth-intensive applications. Services can be switched or broadcast, symmetrical or asymmetrical, unidirectional or bidirectional, and provided with different bandwidth granularities. These demands are being met by the deeper penetration of optical fiber in access networks and by the wide deployment of Fiber-To-The-X-point (FTTX), where the X refers to the point that the fiber is terminated and can be in a nearby cabinet, less than 1 km from the subscriber (FTTCab), or closer to the subscriber up to the Curb or Building (FTTC/FTTB) serving typically a small number of subscribers (8 to 64) or finally to the Home (FTTH). FTTH is the fastest-growing global broadband technology, with significant deployments in Asia, Europe, and North America.

Finally the total power consumption in telecommunication infrastructures is becoming a critical issue for the sustainability of Internet services. Currently, a large national telecom network in Europe typically consumes around of 150-200 Gigawatt/hour a year. Actually, around 9% of the total annual OPEX is due to power consumption. Such figures are of great importance since most telecom operators spend around three times more in OPEX than CAPEX. A network paradigm exploiting power-hungry machinery to accomplish the necessary tasks will face difficulties to retain this mode of operation in the years to come. Therefore architectures employing passive elements for bandwidth distribution and integrated functionality leading to a reduction in the number of active nodes are the only mean to empower next generation network infrastructures

3. Current state of the art and its limitations

In response to the demands mentioned above, Passive Optical Networks (PONs) have emerged as a promising access technology that offers flexibility, broad area coverage, and cost-effective sharing of the expensive optical links compared to the conventional point-to-point (P2P) transport solutions. Passive splitting results in a tree-topology and consequently in a network architecture based on broadcast downstream transmission and an arbitrated multiple access mode on the upstream direction based on time division (TDMA). It is worth noting that this upstream multiplexing technique implements distributed buffering in leaf nodes called Optical Networking Units (ONUs) and centralized arbitration based on the Medium Access Control (MAC) protocol implemented at the root where the so called Optical Line Termination (OLT) resides. In addition, PONs inherently concentrate traffic and greatly reduce the number of input ports in the access multiplexer, both important in order to reduce cost, power consumption and real-estate requirements at the network provider's central office.

3.A. TDM-PONs

Recently both ITU and IEEE have standardized solutions for Passive Optical Networks operating at gigabit per second line rates and optimized for the transport of packet-based traffic to improve the efficiency of previously standardized broadband PONs, which used the ATM cell as the data transport unit. In January 2003, the GPON (Gigabit PON) standards were ratified by ITU-T and were included in the G.984.x series of ITU-T Recommendations ([2, 3]). At the same time IEEE, through the activities of Ethernet in the First Mile (EFM) 802.3ah group, has standardized a Gigabit Ethernet-friendly technology ([4, 5]) called Ethernet PON (EPON), with the objective to leverage the great success of Ethernet as a LAN technology and exploit the economies of scale that the dominance of Ethernet has generated. The operation of both GPON and EPON protocols share some common mechanisms ([6]) that have been deployed already since the first generation of ATM-based PONs (APONs or alternatively named in ITU-T G.983.1 standard [7] Broadband PONs – BPONs). These mechanisms include the following:

1. An ONU addressing scheme at Layer 2 of the protocol stack (Transmission Convergence layer)
2. Burst upstream transmission in variable time windows determined by the OLT for each ONU
3. Multiplexing of data in the form of Layer 2 packets (frames –either following the Ethernet encapsulation in EPON or the GPON Encapsulation Method - or ATM cells) also providing support for packet delineation (as well as segmentation and reassembly in the case of GPON)
4. An in-band signaling scheme for the exchange of control messages and executing the MAC protocol (i.e. MAC messages are interleaved with packet data transmission either in the form of encapsulation headers or in the form of single discrete packets identified by a specific protocol identifier in the respective header field).

Although all the above mentioned PON technologies and standards focus on the efficient design of optical transmission systems for providing access to enterprise and residential users to broadband backbone networks, they present the inherent features of the legacy store-and-forward Internetworking model that packet switched networks have adopted based on the efficiency and maturity of electronic switching technology. Current standardized technologies determine the operation of the optical access segment in isolation taking into account only specific interfaces to the user premises equipment as well as to the edge nodes of a backbone network. Therefore they are limited to addressing only the utilization of single wavelength transmission and multiplexing of data between the ONUs and the OLT. Data forwarding to and from the ONUs and the OLT is still performed by means of legacy networking technologies. Today the most common scenario is to employ PONs as an access segment extension of a metro ring to replace costly point-to-point access multiplexers as shown in Figure 1 (a). Metro networks are still based on a mix of SDH/SONET or OTN and CWDM or DWDM technologies and utilizing the mature technology of Optical Add Drop Multiplexers (OADM) for wide-area interconnection. Clearly data forwarding to and from the access network (i.e. between the OLT and the metro node e.g. OADM) requires termination of the wavelength path, optoelectronic conversion and most important per packet processing and buffering in order to implement protocol translation, synchronization, rate adaptation and scheduling of transmissions on the next TDM multiplexed segment.

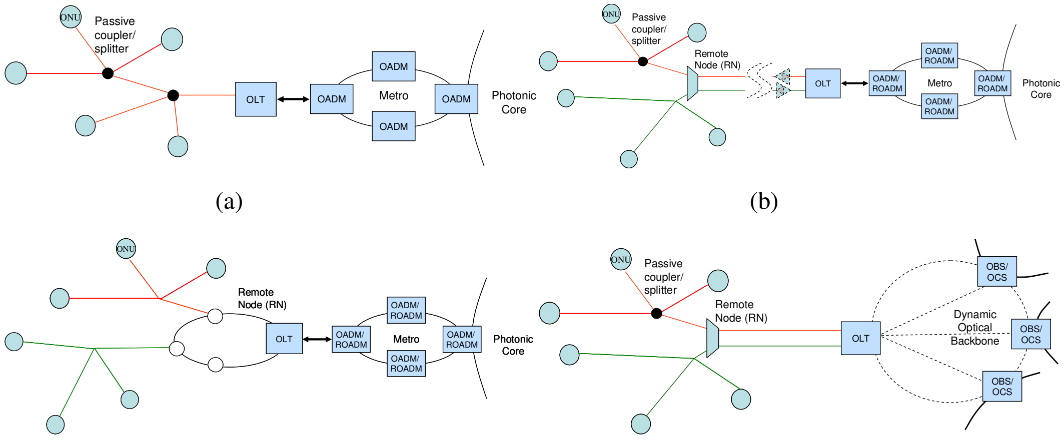
3.B. WDM-PONs

Beyond the single wavelength transmission however, both GPON and EPON already make some use of wavelength division multiplexing (WDM) to achieve single-fiber operation and allow the option of video broadcast via an overlay wavelength in parallel to interactive data services. On the other hand, long-haul and metro networks make extensive use of WDM supporting a typical number of wavelengths from eight to more than 100, depending on the applications. Therefore, there are already several proposals for the evolution of next generation optical access networks to exploit the large number of wavelengths made available by WDM technologies in the future. An interesting application of many wavelength channels on PON is wavelength division multiple access (WDMA), in which either each ONU or a number of ONUs under a passively split segment operate on different wavelengths resulting in the so-called WDM-PON architecture [6-9]. WDM-PONs, possibly complemented by TDMA techniques are considered the next step in the evolution of PONs. They offer higher per-ONU bandwidths, splitting ratios, and maximum reach, as compared to EPON and GPON architectures. 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. They can also offer additional functionality like protection, and they can support various fiber topologies not restricted to physical tree or star structures.

WDM-PONs are considered a promising technology due to their advantages mentioned above and for several years there have been on-going efforts to evaluate and develop appropriate components that could be potentially used in building efficient and robust WDM-PONs. However they still lack a critical factor, which is the existence of consolidated technologies and standards that could lead to commonly acceptable network control mechanisms and core network interfaces for interoperability. The large interest that WDM-PONs have attracted lately focuses around a variety of approaches. The differences between approaches merely depend on the technology alternatives for introducing the potential of WDM and the implementation of appropriate wavelength allocation mechanisms in a manner that can exploit the inherent features of specific photonic components that have been proposed in the literature and experimentally evaluated. Each solution is based on specific assumptions about the potential resource utilization, system design complexity, cost and performance. Furthermore the performance of each proposed solution can be evaluated taking into account several metrics that may range from mere development and production cost to robustness and stability of operation in the field as well as overall network cost of operation and maintenance (affected by factors like capacity, reach, configurability and interoperability). In this respect it is not yet clear whether some major commercial or technological drivers will finally prevail that may favor a specific approach.

A basic classification of the several proposals for WDM-PONs that have been made in recent years can be initially based on the trade-off between design cost and flexibility in resource allocation and utilization. It is worth noting at this point that the major impact of each component technology on network performance apart from system cost is the flexibility to dynamically allocate capacity (i.e. wavelengths) for upstream and downstream transmission to specific network end-points depending on the overall network topology. The main motivation behind WDM-PONs is their potential to increase at the same time the maximum split and therefore the maximum number of customers reached through the same OLT and overall access network capacity. The topologies that have been studied depend on the use of the so-called Remote Nodes (RNs), which are used as wavelength (de)multiplexing points. In legacy PONs fiber and wavelength sharing was based on passive splitters/couplers (which may still work in WDM-PONs without the benefits of increased split and reach though). In WDM-PONs as a basic multiplexing stage most frequently, a wavelength routing device (like an AWG, [6-10, 12] used in a single or in multiple stages) or wavelength filters with specific properties also including power couplers are used [11], since the power loss of these components is significantly less than that of simple passive couplers. Depending on the WDM multiplexing stages and RN interconnection schemes the above options can result in maintaining the tree-shaped network topology as the example shown in Figure 1 (b) or in a hybrid ring-tree topology as the example shown in Figure 1 (c). Further low-cost solutions proposed for the basic elements of WDM-PONs include proposals for using Coarse DWM (CDWM) [6-9, 12], which allows ONU design to be based on standard, low-cost CWDM small-form factor pluggable (SFP) tranceivers and colorless ONUs (either following a spectrum slicing or shared source/seed approach). The term colorless ONU refers to a reflective device to modulate the upstream data applying an optical carrier sent by the OLT; this technique does not require any light source at the ONU and allows ONUs to be identical.

Although the technologies presented so far can support a passive outside plant, they have specific limitations with respect to how the network capacity can be allocated. For example AWGs have specific spectral properties and once deployed in the field dynamic capacity upgrade is not possible. The same stands for reflective ONUs as well as specific proposals for sharing components at the OLT where also upstream transmission requires appropriate batch scheduling ([13]). Therefore in case the customer bandwidth requirements vary, the network should reconfigure for providing efficient and dynamic bandwidth allocation amongst customers in each PON network. Obviously this requires more complex components that can provide the required functionality. Until recently efforts have focused around building long reach PONs via amplification and cost-effective coloured optics in ONUs ([14]) that can allow efficient and lower-cost backhauling WDM (shown as an option with dotted lines in Figure 1 (b)). High-end solutions to deal with these requirements should ultimately employ active components at the RN, possible based on λ-agile switches, and tunable components (filters/transceivers or even bank of transceivers) at the ONU side.



(a) (b) (c) (d)

Figure 1: Passive optical network evolution and interconnection to optical backhaul networks

3.C. WDM metro and core networks

Most WDM-PON or long-reach PON solutions presented up to now still focus on the technologies to upgrade the access network segment and are based on the underlying assumption that the WDM domain of the access segment terminates at the OLT, where traffic is converted to the electronic domain and switched through legacy technologies to the backbone transport network. On the other hand, mature optical metro architectures allowing for all optical data transmission through WDM ring or mesh networks and for dynamic allocation of the wavelength (based on some TDM multiplexing scheme) have been demonstrated. Reconfigurable OADMs are the key components in such architectures, while switching is either based on variable-size bursts or on fixed-size slots enhancing utilization of the available bandwidth. An example of this paradigm shift has been the pioneering work of the IST-DAVID [17] in Europe followed by HORNET [18] in the US. The IST-DAVID studied a metropolitan network using fixed size, synchronized, slots. The main drawback of this approach is poor scalability. The important feature of these architectures is the all-optical transport of data throughout the metro segment, since access arbitration to the shared wavelengths takes place through the execution of a control plane protocol exchanging protocol messages on a dedicated communication channel; thus relieving the burden of information processing on the rest of the data channels.

Further proposals have been made aiming to extend optical core networks beyond the static TDM multiplexing techniques provided by legacy technologies like SDH/SONET exploiting the possibilities of new optical switching technologies, which can be implemented directly in the optical domain and limiting the requirement for information processing of data flows. Several approaches are usually collectively characterized as “IP-over-WDM” since they adopt a two-layer OPR node consisting of an IP router and a WDM optical crossconnect (OXC) with a GMPLS control plane [19-21] allowing for the wavelength channels to be set-up and released under a distributed control mechanism. This approach has the potential to be the first one to demonstrate an integrated (peer-to-peer) control plane to perform optical circuit switching (OCS) whilst it solves aspects of QoS performance restrictions like guaranteed service delivery and high availability level with long holding times. On the other hand, essentially it is suitable only for relatively slow reconfiguration times i.e. for networks exhibiting rather slow variation of their traffic profiles meaning that in those networks the wavelength channels are already well-groomed so statistical multiplexing gains are moderate. In general, a pure OCS system is not bandwidth efficient since the majority of the traffic flows do not transfer a fixed continuous amount of data over long periods (minutes to months) but are rather bursty and solutions to implement photonic transport protocols that support statistical multiplexing over fiber links are sought.

Most recent approaches focus on all-optical packet/burst switching (OPS/OBS) proposed as a method for achieving packet-format transparency and fine switching granularity, while at the same time taking advantage of new optical techniques to overcome the limitations related to optical to electrical and back to optical (o-e-o) conversions ([22-24]). The principle of OBS operation is simple: the source node sends a Burst Header ahead of each data burst in a control channel to prepare all nodes along the data path for the following burst, which therefore need not be buffered on the way to its destination. Its strength lies in achieving multiplexing gain directly in the optical domain, while keeping control processing in the electrical domain ([24]). Its weakness is rather heavy burst loss for most of the protocols proposed up to now in the literature, except at very low utilization levels due to its ambitious on-the-fly switching. In most proposed architectures, packet traffic may be aggregated and possibly segmented at the system periphery creating fixed size data packets (slots). Slotting can reduce the collision probabilities in OBS networks, by avoiding the considerable waste of partial collisions.

Identifying the need to integrate the new interconnection architectures, data forwarding and switching paradigms introduced in the realm of optical networking technologies only recently some proposals have appeared towards an integrated infrastructure that can address the requirement of WDM access and switched core optical networks based on the state-of-the-art technologies discussed above. These approaches can be collectively described by Figure 1 (d), where the main characteristic is a collapsed hierarchy of optical access and metro networks into a unified dynamically optically switched network infrastructure. In an early work in [27] the authors have actually discussed an all-optical metro and core network integration under a unified operation in an OBS mode. This solution actually focused on ring interconnected metro networks, which is a common case in existing networks and presented an architecture that employed distributed buffering for implementing burst assembly and data forwarding through ring nodes called Optical Burst-Add and Drop Multiplexers (OB-ADM). This architecture though does not address the current and next –generation optical access networks in the context discussed above. In [28] the authors proposed an architecture named STARGATE including an extension to the EPON protocol to accommodate an integration of currently deployed EPONs again with ring interconnected optical backhaul networks. STARGATE aimed at an all-optical integration of Ethernet-based WDM EPON and WDM upgraded RPR networks that would result in an Ethernet-based optical access MAN. According to STARGATE the upgrade in EPON access networks to WDM PONs should be based on technology neutral ONUs that would negotiate, during a registration phase, their capabilities and AWG based wavelength routing. While WDM-PON and WDM metro in STARGATE is envisaged through a non-transparent EPON-RPR gateway additionally a transparent optical interconnection overlay is proposed based on optical bypassing of a specified set of wavelengths at the PON side, which is then directed to a wavelength routed WDM metro overlay network of star topology. Finally in [29] a new all-optical access–metro network interface based on OBS is proposed. This last proposal is based on the use of reflective ONUs, a centralized MAC and a burst switching multiplexer called OBS-M, which offers optical cross-connection, wavelength conversion and data signalling interfacing access and metro networks. The authors in [29] describe a viable technology in terms of components used, which is indeed interoperable with OBS but do not extend their description to describe traffic aggregation and burst assembly algorithms that could optimize burst transfer over the optical core network.

4. Proposed integrated network architecture

Based on the current state-of-the-art and the still open issues and limitations that have been discussed above we reach a number of conclusions, that have been taken into account in the proposed architecture described in this section. Next-generation optical transport networks will still have to accommodate multiple segments and an appropriate new hierarchical organization is sought. This new network hierarchy should adapt to the requirements of the ultra high-capacity these networks can provide as well as the specific requirements of dynamic resource allocation and switching at an appropriate granularity in the optical domain. Hybrid WDM-PONs will supersede TDM-PONs as soon as the service requirements and customer demands justify the cost for transition and will transform the legacy access network segment. Their new capacity and transportation mechanisms require a rethinking of the integration of this new kind of optical segment, which may span the boundaries of legacy access and metro networks and must accommodate the requirements of dynamic service composition and delivery and efficient end-to-end communications. In order to achieve this, we need a shift towards an architecture that is compatible with dynamic optically switched networks and can be interoperable with technologies like wavelength routing and optical packet/burst switching.

As evident from the discussion in the previous section there are several technologies that can be used in WDM-PONs. In this work we do not propose any new technological component to define a new physical layer of access networks integrating WDM and PON technologies. On the contrary we adopt the concept of [28] assuming that most probably several alternatives will finally compete in the commercial arena and an architecture should accommodate them in the broadest possible way. In addition already proposed photonic components like those described in [9-11, 29] may provide the technology platform on which WDM-PONs may be based upon.

For the core optical transport though we have proposed in the past ([32]) a generic architecture for a multi-granular, multi-layer, connection-oriented OPR which can accommodate aspects of existing NG-SDH/ SONET systems as well as other advanced L2 framing solutions, in the periphery [17, 30- 31] in an integrated manner. The main motivation behind this work is that the aggregation and switching nodes of the next-generation optically switched networks should introduce a number of transportation and switching entities in the optical layer, bridging the bandwidth granularity between that of an IP-packet/Ethernet frame and that of a WDM channel whilst facilitating efficient aggregation and grooming, as shown in Figure 2.

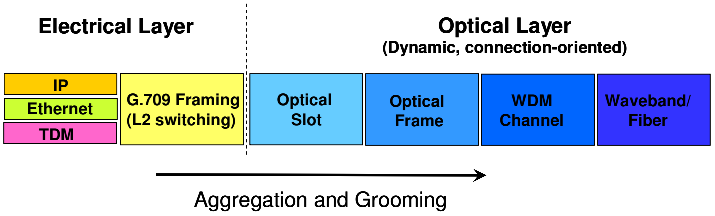


Figure 2: Traffic aggregation and frame encapsulation for efficient optical switching

While in general the technologies and components investigated in the literature (e.g. in [28, 29]) may be used for the integration of WDM-PONs and core networks, the intricacies of the control plane design towards an end-to-end efficient optical network coordination have not yet been adequately addressed. The main consideration in this case is that neither wavelength routing techniques (as e.g. used in [28]) can scale when fast reconfiguration is widely requested, nor OBS switching techniques ([22-23, 33-34] as used e.g. in [29]) -while extremely dynamic in the allocation of network resources- can scale to large optical networks due to their poor performance in terms of burst loss probability. Furthermore legacy TDM-PON MAC protocols are operating with a byte/packet granularity, which are not appropriate for the required burst/frame granularity of optical core networks. Therefore the frame aggregation process (also called burst assembly in OBS) is vital in terms of end-to-end traffic management and network control. In order to accommodate the traffic aggregation concept shown in Figure 2 we have proposed in [35] a network hierarchy called CANON initially to address these considerations in dynamically switched core optical networks proposing a hierarchical organization employing a clustering architecture. In [36] we demonstrated the performance improvements of the CANON architecture when clusters representing autonomously administered periphery network segments following a ring topology are interconnected through an arbitrary topology core employing dynamic multiplexing of traffic over the cluster rings and forwarding through pre-provisioned connections over the core network. In [37] we also compared the performance of CANON architecture with completely dynamic reservation based techniques like OBS over the core network and concluded that even in this case the two-layer hierarchical organization combined with synchronous frame switching may lead to significant performance gains. In this work we propose a compatible to the CANON architecture WDM-PON based access and core network integrated architecture, which can be implemented mainly by extensions of the control plane design and MAC protocol implementation. In this work we also adopt the concept of fixed-size frames (with a sized F in the order of several milliseconds and at least multiple of the access network segment round trip delay) as a basic unit for transport over the core network.

4.A. Node architecture and interconnection scheme

The network architecture we consider is shown in Figure 3, which can be classified under the generic high level architecture shown in Figure 1 (d). As mentioned above we consider that ONUs may have different properties and the only requirement is that they can report their capabilities to the OLT and mainly the transmission wavelengths they may share in the upstream direction (as e.g. proposed in [28]). Any type of RN should also be supported. The core implementation of this integrated architecture is based on the resource allocation controller, which resides at the OLT and is responsible for the implementation of upstream frame aggregation, resource reservation over the core network and transparent frame forwarding in both downstream and upstream directions.

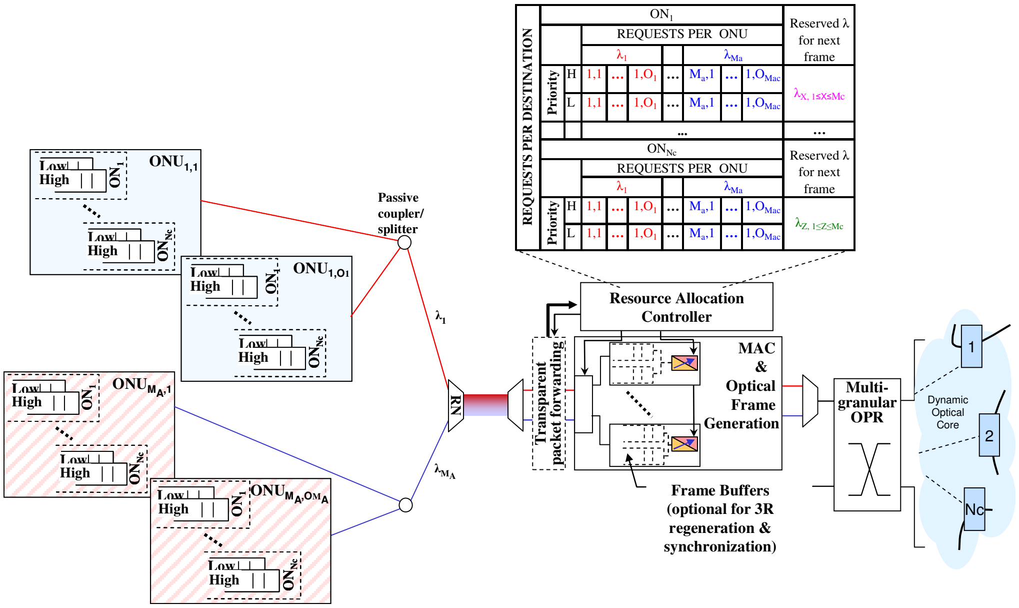


Figure 3: Unified optical transport network based on the integration of WDM, dynamic optical routers and passive optical network segments

The WDM access segment will support a number of wavelengths denoted as M_a while the potential number of wavelengths that can be used over the WDM core is denoted as M_c. Up to O_i ONUs may be sharing the same upstream wavelength i ($i \in [1, M_a]$) in a TDM fashion, whereas specific ONUs can also employ more than one transceivers and communicate over multiple wavelength if additional capacity is required. The access segment as shown in Figure 3 is interconnected to an optical transport network comprising of Nc optical nodes (ONs). The point of integration is the upgraded OLT shown in Figure 3 providing appropriate interfacing to an OPR following the architecture of [32] and transparently aggregating and forwarding traffic by means of an extended control plane, which implements access segment arbitration in coordination with resource allocation over the network segment. The set of notations used in this manuscript is listed in Table I and the details of the required extensions in the control plane design affecting also the distributed buffering architecture are discussed in detail in the following section.

TABLE I: NOTATION

Abbreviaton	Parameter/Function
F	Frame duration
M_c	Number of wavelengths for data transport over the WDM core network
M_a	Number of wavelengths for data transport over the WDM-PON network
N_c	Number of optical nodes (ONs) in the core network
C_i	Capacity of upstream wavelength i ($i \in [1, M_a]$)
O_i	Number of ONUs sharing upstream wavelength i ($i \in [1, M_a]$)
$R_{H,ijk}$	Reported High Priority traffic from ONU j ($j \in [1, O_i]$) operating at wavelength i ($i \in [1, M_a]$) and destined towards core node k ($i \in [1, N_c]$).
$R_{L,ijk}$	Reported Low Priority traffic from ONU j ($j \in [1, O_i]$) operating at wavelength i ($i \in [1, M_a]$) and destined towards core node k ($i \in [1, N_c]$).
T_{Hk}	Value of timer triggering generation of frame carrying High Priority traffic destined towards core node k ($i \in [1, N_c]$).
T_{Lk}	Value of timer triggering generation of frame carrying Low Priority traffic destined towards core node k ($i \in [1, N_c]$).
T_{HMAX}	Maximum frame assembly waiting time for High Priority traffic.
T_{LMAX}	Maximum frame assembly waiting time for Low Priority traffic.
U_{MIN}	Minimum acceptable frame fill level for early frame generation.
T_{MIN}	Minimum waiting time for early frame generation.

4.B. Control plane design

In order to proceed to describing the implementation details of the proposed architecture we should first clarify that the transparent integration and packet forwarding we envisage is not aiming as a first step to avoid optoelectronic conversion as done in [29]. Since wavelength switching should also take into account network topology and path information, completely transparent forwarding in the optical domain without 3R regeneration will be hard to accomplish due to physical layer constraints. Furthermore from a traffic management point of view optical switching in the form of variable size bursts suffers from even further performance degradation ([38-39]). Therefore a mean of synchronized operation and network-wide scheduling of transmissions in order to avoid channel collisions as proposed in [35-36, 40] is required. The transparency is maintained though in the domain of per flow information processing, since no inspection and processing of the data traffic carried over the transport network is required in order to take forwarding decisions. The proposed architecture can maintain this level of transparency, which can result in efficient aggregation of data at the requested capacity and interoperability with dynamic optical core networks operating in a frame synchronous mode with all the subsequent performance enhancements.

In order to achieve this, the only additional requirement is to provide a mechanism for route and network topology discovery so that node addressing information can be maintained in each node of the integrated network (both ONUs and OLT as well as core ONs). This however is a requirement of any Layer 2 technology. By having this information packet classification and per flow queuing can only be retained at the ONU side, which now represents the edge node of the integrated optical network and the interfacing point to legacy packet switched networks. Depending on their destination in the optical core network, packets at the ONU side are stored in Nc discrete First-In-First-Out (FIFO) queues. Further classification can be employed to implement prioritization in order to support discrete Classes of Service (CoS); in this work like in [36] we consider two CoS queues discriminating between High and Low priority traffic. Queue status reporting from the ONUs towards the OLT in order to implement dynamic bandwidth allocation (DBA) takes place through a control channel. Unlike reservation protocols for WDM metro rings ([17-18, 36]) a dedicated wavelength allocated to the exchange of control information may not be justified for cost reasons. In this case control information can be transmitted "in-band" as in [29] following the typical TDM multiplexing of existing PONs. Note that the processing of messages carried over the control channel still does not violate the transparent data forwarding in the sense laid out above, since the control channel represents a clearly identified sub-channel, which can be converted (in an add/drop sense) and processed independently of the rest of the data flow.

Data arrivals at each ONU queue (also representing the destination optical node ON across the optical core) are reported through appropriate MAC messages (as e.g. in [28]) transmitted through the control channel after periodic polling of ONUs by the OLT in time windows of duration Dm (as e.g. in [6, 29]). These reservation requests are stored in a matrix in the Resource Allocation Controller as shown in Figure 3 per CoS, destination ON, originating ONU and associated upstream wavelength in order to dynamically schedule upstream allocations. The objective of the allocation is to aim for high fill-up of data frames to be generated and forwarded towards the optically switched core, while relying on timers to enforce upper limits to the service delay in each direction (denoted as T_{HMAX} and T_{LMAX} for each CoS respectively in Table I). If the offered load exceeds serviceable capacity, it can become impossible to create frames for all timeouts and for this reason admission control at the entry of the system by means of Service Level Agreements (SLAs) and policing is relied upon to ensure that long-term overloads are prevented. This is crucial for first priority traffic, which is expected to be about 20 to 30% of the total load due to higher tariffs and blocking by admission control. But these issues are no different to any network serving QoS-sensitive traffic and will not be further elaborated.

The selection of the wavelength to be used for frame forwarding over the core network can follow different schemes. It can be statically allocated, if capacity is abundant and cost and scalability are not considering limiting factors, or semi-statically provisioned through a wavelength routing (OCS) approach. On the other hand they can be dynamically allocated ([29, 37]), in which case either a one-way reservation can be attempted ([23]), as shown in Figure 4 (continuous line) in case loss probability is not considered a limiting factor, or finally implementing a two-way reservation (dotted line) for guaranteed service delivery, in case end-to-end delay is not considered a limiting factor.

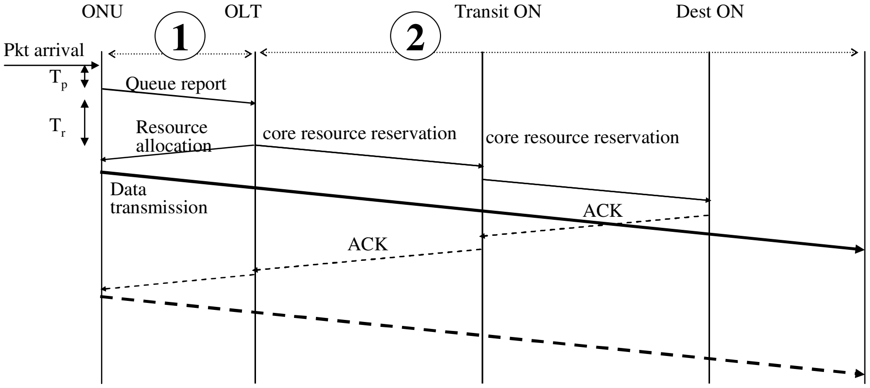


Figure 4: End-to-end resource reservation over the integrated access and core optical network

The additional delays introduced by this procedure include the inherent to PONs polling delay determined by the Round Trip Time (RTT) as well as the frame assembly delay (denoted as T_r in Figure 4), which may range from RTT to T_{MAX}. The frame assembly procedure and initiation of reservation over the core is performed under the following rules.

- For each destination ON upon the receipt of the first request from an ONU to reach this destination a timer is set (either T_H or T_L depending on the CoS of the request). Whenever any of the timers reaches the maximum acceptable value (T_{HMAX}/T_{LMAX} respectively) frame generation is triggered irrespective of the total amount of requests
- Whenever the sum of the requests expressed by $R_{tot} = \sum_{i=1}^{Ma} \min\{C_i, \sum_{j=1}^{Oi} R_{H,ijk} + \sum_{j=1}^{Oi} R_{L,ijk}\}$ exceeds the frame capacity i.e. $R_{tot} > F$, a frame generation is procedure is initiated as shown in Figure 4. In case $R_{tot} > F$ high priority requests $\sum_{i=1}^{Ma} \min\{C_i, \sum_{j=1}^{Oi} R_{H,ijk}\}$ are served with a strict priority and in case they also exceed the available capacity a fair sharing distribution among them (as in [5]) is implemented. Spare capacity is further shared in the same manner to serve the remaining low priority requests $\sum_{i=1}^{Ma} \min\{C_i, \sum_{j=1}^{Oi} R_{L,ijk}\}$
- Finally in case R_{tot} exceeds a minimum acceptable frame-fill level U_{MIN} and a minimum waiting

time for frame assembly T_{MIN} has elapsed again a frame generation is triggered, in order to expedite data forwarding at the cost of an acceptable level of frame underutilization ($U_{loss}=F-U_{MIN}$)

Obviously since frames multiplex data from ONUs residing at different WDM segments and using different wavelengths, wavelength conversion is required for each destination channel. This can be indirectly achieved when upstream bursts are e-o converted and buffered in a local per-destination frame buffer as shown in Figure 3 using a fixed transmitter at the output of the buffer. Note that this assembly process could even be performed on-the-fly through the use of tunable wavelength converters for each channel to the core network implementing an all-optical integration as in [29] in the way shown in Figure 5. The scheduling burden though for sorting variable burst transmissions in subsequent time intervals would increase and depending on the heuristic algorithm implemented may cause a decrease in frame utilization.

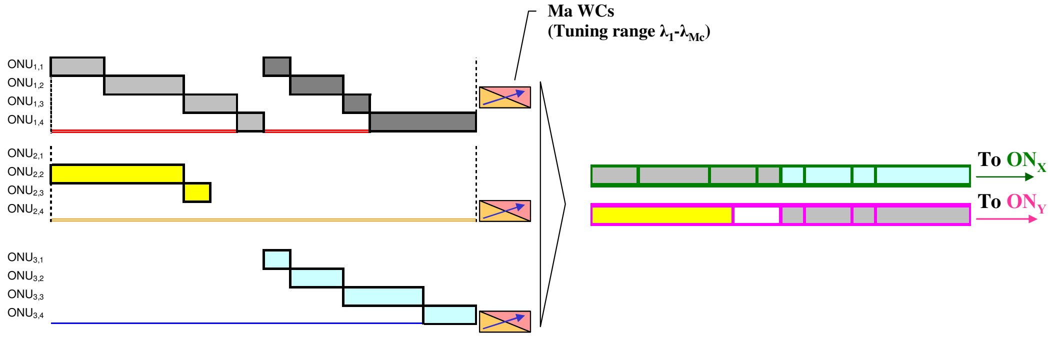


Figure 5: Example of all-optical integration (consecutive burst allocations for on-the-fly frame generation and forwarding)

5. Performance evaluation

The performance of any proposed integrated architecture should be evaluated against the following metrics:

1. Overall network design cost (including power consumption and ability to scale)
2. Resource utilization
3. Delay performance
4. Loss performance

Regarding the first metric cost reduction is an inherent feature of the proposed architecture, since access-core metro integration allows the extended reach of PON optical transport networks and interconnection to optical backhaul networks through a single interconnection node. In case of path termination and discrete network protocols, like in the case of a WDM-PON interconnection with an OBS core network, the gateway functionality should be provided by an OBS edge node, causing the unnecessary o-e-o conversion and per packet processing (i.e. classification, encapsulation and scheduling) in both the OLT and OBS edge nodes (as is the case depicted in Figure 1 (b) and (c). OPEX savings come at the cost of an increased control protocol complexity and queuing policy at the ONUs in the access segment, which is not expected though to significantly affect their overall cost. This concept of a light optical core with intelligence concentrated in edge nodes is common across several proposals ([28, 37, 40]). On the other hand regarding the ability to scale the architecture achieving the networking service providers' requirements to "pay as you grow" it is worth noting that, while not interoperable with legacy TDM and WDM PONs the proposed architecture can be implemented as a gradual network upgrade, without requiring the replacement of installed equipment. Legacy equipment (e.g. GPON or EPON systems) will inevitably require traffic termination, processing and burst assembly at the OLT side, which can however be interfaced to the same edge OPR as an additional port. The deployment of ONUs supporting the proposed enhanced control plane and traffic management scheme will offload the majority of electronic processing and will enable an access network capacity upgrade without the cost of legacy electronic packet processing and switching at the optical network edge node.

Regarding the delay performance of the proposed architecture it would only make sense to compare it to a non-integrated approach so as to evaluate the introduced differences of the frame aggregation policy. Therefore, we developed a simulation model using the OPNET simulator implementing the architecture shown in Figure 3 for M_a=4 and O_i =16 (i.e. 64 ONUs in total) for all upstream wavelengths I, T_{HMAX} =3 frame durations. Varying the parameters N_c,, U_{MIN} and the offered load (expressed as a percentage of the capacity of each upstream wavelength) we measured the incurred access delay and corresponding frame utilization in different scenarios. Traffic arrival patterns for the high priority class were simulated by constant bit rate sources generating short fixed-size packets periodically (a model compatible with voice traffic). The traffic mix included on average 30% high priority traffic. This service class is expected to serve mostly traffic from real-time services also associated with a higher tariff limiting its contribution to the overall network load as argued in [5]. For the low priority respectively traffic sources were of ON-OFF type (modeling self-similar Internet traffic), with a burstiness factor of 8. Given the choice of Ethernet as the dominant client protocol the widely used tri-modal distribution was adopted for the packet size. This is based on extensive actual measurements which showed it to be a quite good approximation of IP applications originating in Ethernet networks. It consists of packet sizes of 64, 500, 1500 bytes appearing with probability of 0.6, 0.2, and 0.2 respectively according to [42]. The destination of each packet was randomly selected to be a remote ON with uniformly distributed probability. Resource reservation inside the core network (i.e. communication between the ONs) for the shake of simplicity has been considered based on statically provisioned wavelengths from each ON to each other, creating a full logical mesh.

We compared this architecture with a non-integrated one, where the OLT MAC and upstream data transmissions are scheduled independently from the frame switched core network and without knowledge of core network routing and resource allocation decisions. In this second case upstream data are transmitted under the guidance of the OLT taking into account only the requirement for fair sharing of resources among all competing ONUs (denoted hereafter as “Uniform” allocations). Upstream bursts are forwarded to a frame aggregation unit, where FIFO queues per destination are implemented and where data inspection, classification and frame assembly is performed. Frame generation decisions in this second case are based on the same T_{HMAX}, T_{HMIN} and U_{MIN} thresholds.

In Figure 6 below we show the frame utilization level (i.e. fill level expressed as the percentage of the frame duration occupied for data transmission) for 90% total offered load varying the number of potential ON destinations and the minimum utilization threshold U_{MIN}. As evident from Figure 6 the integrated architecture can achieve higher frame utilization, when a more relaxed threshold U_{MIN} is used. The only cases where equal performance is observed are i) the case of very few destinations (where all upstream traffic is distributed among them and suffices to completely fill frames destined towards these destinations) and ii) the case of strictly dictated lowest acceptable frame utilization U_{MIN} close to 100%, where there is no option but to wait for timer expirations to trigger frame generation resulting in similar behavior in both cases. In general since the non-integrated architecture favors upstream transmission uniformly (or weighted if required in a different scenario) distributed between ONUs without knowledge of the destination of the transmitted packets, it takes longer to aggregate acceptable amount of traffic to justify a frame generation. Thus, when timers expirations dictate early generation due to delay tolerance limitations, frame underutilization may occur.

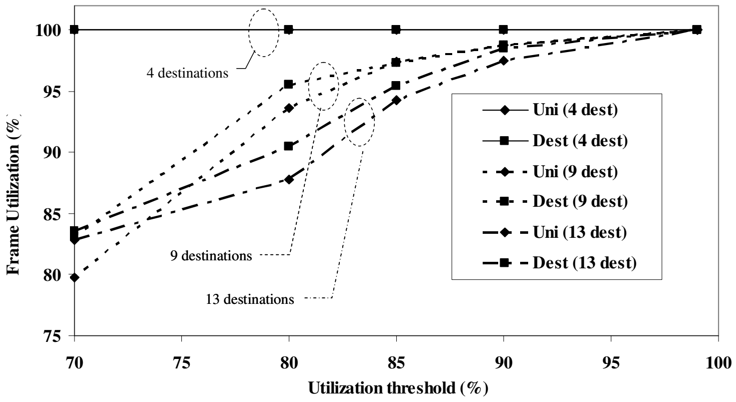
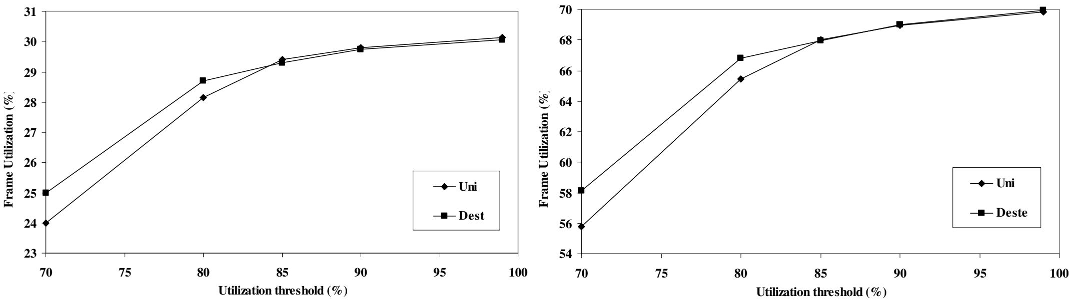


Figure 6: Average frame utilization (frame fill level) vs. U_T and *Nc* (offered load 90%)

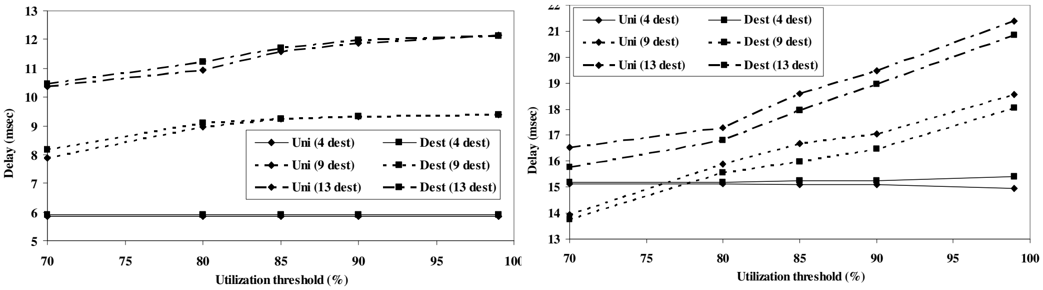
In Figure 7 we show in detail the absolute percentage of the frame occupied by high priority traffic (a) and low priority traffic (b). Obviously these two figures in each case sum up to the total frame utilization shown in Figure 6. Additionally the contribution of each CoS in frame utilization is determined by the percentage of each traffic source type in the overall offered load, as described above.



(a) (b)

Figure 7: Frame fill level for each priority (a) high priority (b) low priority traffic vs. U_T (offered load 90%, *Nc*=9)

Finally in Figure 8 we present the average access delay among all ONUs from packet generation until corresponding frame transmission (i.e. a frame containing this packet) from the OLT for high priority (a) and low priority (b) traffic. The same observations that explain the behavior of the integrated MAC with respect to the frame utilization shown in Figure 6 can also be used in the analysis of the delay incurred by the two schemes. In the case of a small number of destinations and corresponding FIFO queues or frame assembly buffers, frames can be assembled with very low latency since the upstream load is distributed among few queues, which frequently fill-up triggering frame generations in both cases. For a higher number of destinations and when lower utilization thresholds are used in order to limit delay for high priority traffic, the non-integrated architecture presents a hardly visible decrease in the delay of high priority traffic, whereas the integrated architecture presents an improvement in the delay of low priority traffic. This is due to the inherent operation of the allocation mechanism of the integrated OLT to favor transmissions from queues that can lead earlier to frame generation, when enough traffic towards a specific destination has been aggregated. Since low priority traffic represents the great majority of offered load in this scenario (70%) it is more frequently given the opportunity to transmit in order to fill-up frames and improve utilization as observed in Figure 6.



(a) (b)

Figure 8: Average access delay for high priority (a) and low priority (b) traffic

6. Conclusions and future work

The architecture we presented in this paper leads to a transparent core-access integration, supporting optical flow/packet transport and end-to-end service delivery capability, overcoming the limitations of segmentation between access, metro and core networks and domains. A unified optical node consolidation integrating WDM and TDM multiplexing techniques can efficiently utilize state-of-the-art photonic components to develop an optical transport employing both passive optical networking with optical packet routing techniques in an interoperable way. The main innovation is the extension of the control plane and unified resource allocation, so as to minimize the cost of per packet processing, which cannot be tolerated in photonic backhaul networks. The proposed architecture addresses the above by optical burst aggregation over passively split optical access networks employing hybrid WDM-TDM multiplexing into fixed-size containers called frames. This frame aggregation technique can exploit efficient synchronous switching technologies and achieve high utilization of optical core networks. We evaluated this architecture in comparison to typical approaches that have been proposed for dynamic resource allocation utilizing burst switching techniques and have shown that it can better utilize network resources at the cost of a limited increase in delay. More significant performance gains are expected when dynamic resource allocation over the core network is performed, which is currently work in progress. By extending our simulation model to incorporate a fully dynamic optical core we envisage to demonstrate the effectiveness of framing as an encapsulation and switching unit, compared to variable length burst assembly and switching techniques without end-to-end network coordination. Additionally be building an end-to-end model we will be able to measure the effect of downstream blocking in the shared access segment and evaluate its impact on end-to-end performance. Finally if the scenario of all-optical integration is assessed viable appropriate scheduling algorithms should be studied and their impact on utilization should be assessed.

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