All-Optical Remote Node for Cost-Effective Metro-Access Convergence

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Abstract—**The current deployment of optical fiber in the access network will enable the convergence of access and metro networks. This paper proposes a novel remote node architecture for the deployment of all-optical converged metro-access networks meeting the requirements of backward compatibility and single subscriber terminal specification. Moreover, a cost analysis is used to clearly demonstrate the cost-effectiveness of the envisioned system over known alternatives.**

I. INTRODUCTION

Current and foreseeable broadband services already require the availability of unprecedented data rates per individual subscriber, demanding an upgrade of the access segment, which is the most cost-sensitive part of a telecommunications network. It has become clear that optical fiber, which has long been the dominant transmission medium of long-haul and metropolitan networks given its immense transmission capacity over long distances, is getting increasingly closer to the individual subscriber and will constitute the prevailing fixed access infrastructure in the medium term. Significantly, the deployment of Passive Optical Networks (PONs) and other Fiber-To-The-Home (FTTH) approaches is opening the way for optical fibre to be used in both metro and access networks. Hence, these network segments can be said to be converging in terms of their transmission medium.

The growing PON rollouts, already underway in many countries, will likely drive the development of a variety of even more bandwidth-intensive services. Consequently, as subscribers massively adhere to these services, the capacity requirements in the metro side can increase. Traditionally, upgrading the capacity of metro networks is accomplished by installing costly Synchronous Digital Hierarchy (SDH) and Wavelength Division Multiplexing (WDM) gear. However, a more cost-effective upgrade of the metro segment of the network can be on the horizon. More precisely, as the access and metro networks start sharing the same transmission medium, there is the potential that they will converge to use similar technologies, thus benefiting from economy of scale and lower maintenance costs.

A promising approach to realize the abovementioned convergence is to scale the PON system, without necessarily keeping it passive end-to-end, to support with a single infrastructure a large number of subscribers, which were formerly partitioned into multiple access networks [1]. Our previous works have shown the technical feasibility of a converged network based on the future 10G Ethernet PON (EPON) standard and resilient against failures in the former metro segment [2]. Nevertheless, the future bandwidth-hungry services will inevitably require upgrading this network.

A cost-effective and scalable solution to increase the transmission capacity is to deploy WDM in the former metro part, while Time Division Multiplexing (TDM) is kept in the former access part. However, this raises important challenges, namely regarding the backward compatibility with existing xPON systems and the use of a single and low cost specification for all the subscriber terminals. This paper proposes a novel all-optical architecture for the Remote Node (RN), which acts as the interface between the WDM-TDM (metro) network and the multiple TDM (access) networks. In addition, the economic viability of the proposed network is evaluated against competing alternatives, showing that it is the most cost-effective.

II. MOTIVATION AND NETWORK SCENARIO

Nowadays, metro and access are usually two completely distinct networks that differ in terms of technology, protocols and, in most cases, transmission medium. Maintaining these two different networks is complex and expensive and, in addition, the node interconnecting both networks must perform electronic processing of the data traversing from one network segment to the other, in order to produce compliant signals. This means that it must be able to handle the technologies and protocols employed in both networks, making these interconnection nodes rather costly.

The expected large scale deployment of optical fiber in the access segment provides a common transmission medium to both access and metro networks. This motivates the research and development of network architectures for seamless metro-access convergence, given their potential for additional cost savings.

The converged metro-access network will need high capacity at the links traversed by the traffic to/from all of the subscribers (the metro part). A cost-effective and scalable solution to increase this transmission capacity, avoiding the deployment of more optical fibers or the increase of the channel bit rate, is to use WDM. However, because using a dedicated wavelength per subscriber will most likely remain cost-prohibitive in the near future, TDM must still be used in the access part. The use of TDM can eventually have the additional advantage of allowing backward compatibility with existing PON systems. In view of this, the combination of TDM with WDM is envisioned as one of the most promising approaches to design a converged metro-access network that supports current and future broadband services, while using mature and low-cost optical components.

The proposed architecture addresses the challenge of deploying a converged network that can support a larger number of subscribers with higher data rates than that of [2], while simultaneously achieving the following goals:

- Cost-effective metro-access network;
- All-optical transmission between the central office (optical line terminal, OLT) and the user equipment (optical network unit, ONU), enabling a bit-rate and protocol independent network;
- Single specification for all ONUs.

III. REMOTE NODE ARCHITECTURE

In the envisioned metro-access network, a crucial network element is the RN, which provides the interface between the WDM-TDM (metro) network and the TDM (access) networks, as exemplified in Fig. 1. This node adds/drops the upstream/downstream wavelength carrying the traffic from/to the sub-set of subscribers that are attached to it. Given the extended reach of the converged metro-access network, this node must amplify/regenerate the signals. It should also be able to easily support protection mechanisms in order to provide survivability to single failures in the links carrying multiple wavelengths. In terms of backward compatibility and to cost-effectively support the needs of different types of subscribers (assuming they are clustered in different TDM networks), the RN would benefit from being transparent to protocol, bit rate, and modulation format. Another important issue in this network architecture is that the ONUs should be kept simple and, as importantly, they should all have the same specification, that is, the same ONU should work correctly in any end-user location in the network, without being modified for that purpose.

A. Backward Compatibility and Single ONU Specification

In this architecture, the OLT is located in the WDM ring and handles all of the ingress and egress traffic of the network. Since the aggregated traffic from all subscribers is transported over the WDM ring, this network segment is the most critical point of failure. Hence, a two-fibre ring can be used to provide protection against single failures, as described in [2]. In the WDM ring, a unique wavelength pair (λ_D^i and λ_U^i) is allocated to each access segment. However, in each of these segments, the same downstream and upstream wavelengths (λ_D^{1490} and λ_U^{1310}, respectively) are time shared (TDM/TDMA) among its ONUs. This feature, which allows the use of standard-compliant ONUs and the coexistence of different xPON variants (e.g. EPON, GPON), is enabled through the use of all-optical Wavelength Converters (WCs) in each RN.

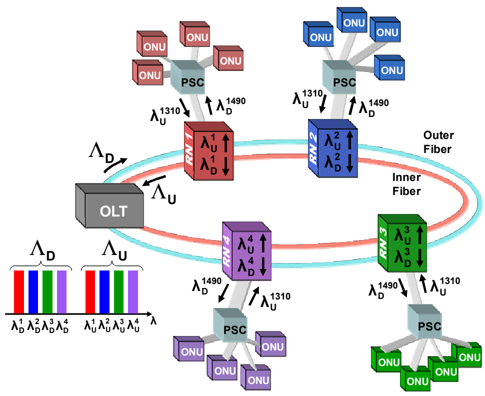

Fig. 1. Network scenario.

B. Building Blocks of the Remote Node

Two RN variants are proposed. In the first one, illustrated in Fig. 2, the RN comprises both Downstream and Upstream Wavelength Converters (DWC and UWC), which are used to convert the wavelength in the WDM ring to/from the wavelength used in the xPON segment. In case the downstream WDM signal is within the xPON receiving band (1480 to 1500 nm), a standard-compliant ONU will be able to detect it, and thus the DWC can be spared. Hence, the second variant of the RN, which can only be used under the abovementioned condition, requires a single wavelength converter. The wavelength conversion can be completely performed in the optical domain [3], avoiding electronic processing of the downstream and upstream signals traversing the remote node. Therefore, fully-transparent end-to-end transmission between the OLT and the ONUs is enabled.

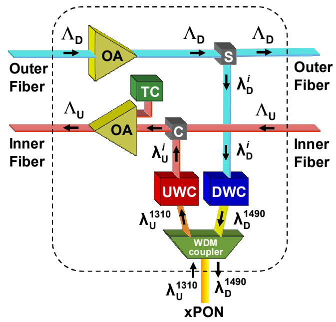

Fig. 2. Remote node architecture.

The RN also contains one Optical Amplifier (OA) per fiber, to increase the available power budget and to compensate for the power losses due to fiber propagation and the other network elements located in the transmission path. Moreover, Transient Control (TC) modules [4] are also introduced as a complement to the OA, to reduce the amplifier transient effect in the time slotted upstream channel. This effect is present when bursty optical signals traverse the OAs, causing high power excursions (transients) at the amplifier output. The consequent power transients can overflow and damage the electric receivers, which could cause service disruption.

The performance study presented in [2], which was made under limitative conditions because only two wavelengths were shared by the large number of subscribers, suggests the physical feasibility of the proposed network evolution, even accounting for the signal degradation introduced by the WCs.

B. Protection Switching

The proposed RN is suitable to implement high-capacity converged metro-access networks, where a transparent end-to-end connection between the OLT and the ONUs is possible relying solely on standardized xPON technology. The WDM segment is commonly supported over a physical ring topology, which can exploit path redundancy to provide highly reliable services. Moreover, in the passive segment, the service can be granted using any of the already available xPON technologies, covering a wide spectrum of FTTx solutions. Assuming the deployment of this scenario in the ISP network landscape, the proposed node configuration perfectly fits in the bridging function of both metro and access segments, allowing the association of low-cost network architectures with carrier-grade services.

The use of protection mechanisms is of extreme importance in metro/access networks, which given their extended reach are very susceptible to fiber cuts caused by negligent ground diggings. With this aim, the network can be designed to assure that the service is maintained to the end-users even if a fiber fault occurs in the ring [2]. In terms of data transmission, the upstream and downstream WDM signals are transmitted in both fibers, in order to guarantee a backup path from where the bidirectional connection can be maintained. To provide this redundancy, and instead of duplicating the transceiver equipment at the OLT, a simple splitter and coupler pair can be used to connect the ring fiber ends. In order to comply with the protection requirements, several elements must be added to the basic remote node architecture, such as optical switches and a WDM coupler/splitter. By convention, assume that the outer (inner) fiber of the ring is used to transmit traffic in the clockwise (counter-clockwise) direction. During the service state, the downstream signal can be extracted from the outer fiber and the upstream can be transmitted over the inner fiber. However, in the presence of a fiber fault, all the remote nodes located after the fault will detect the absence of the downstream flow. After this detection, the state of the optical switches is changed, in order to start inserting/extracting the upstream/downstream signals on the complementary path between the OLT and the remote node. As mentioned before, all the nodes located before the fault can maintain their (service) state, since their service path was not affected by the fault. On the other hand, the nodes positioned after the fault will notice the service interruption in the downstream channel and will perform protection switching.

IV. Cost-Based Analysis

Besides enabling the backward compatible metro-access convergence, the proposed architecture, hereafter designated by WC-RN, should be more economical than the known alternatives that achieve the same goals, i.e. the support of an all-optical metro-access network with a single specification for all ONUs. The most straightforward approach is to use a Tuneable Laser (TL) in each ONU, which will be designated by TL-ONU. Another well-known approach considers the use of a reflective device, e.g. a Reflective Semiconductor Optical Amplifier (R-SOA) [5], as the ONU optical source. This approach is named R-ONU. When compared to the proposed scheme, these alternatives use simpler RNs, as they avoid WCs, but are not standard-compliant, which is a serious drawback for mass deployment. With WC-RN, the ONUs cost/complexity is reduced at the expense of increasing the RNs cost/complexity.

In the following cost-based comparison of the three solutions, it is assumed that there are no relevant differences in the OLT equipment and that all RNs have the same components, with the exception of WC-RN which, in addition, also requires one WC (UWC only) or two WCs (DWC+UWC). The WC-RN approach is assumed to use SOA-based WCs, each made with one SOA and one Continuous Wave (CW) laser tuned in the desired output wavelength. The corresponding ONUs only require a typical receiver (Rx) and a typical fixed transmitter, assumed to be a CW laser coupled with an Electro-Absorption Modulator (EAM), for the sake of comparison. Alternatively, TL-ONU uses at each ONU one Rx and one tuneable transmitter, which can consist of an EAM and a TL, whereas the R-ONU uses at each ONU one Rx and one reflective device, which can consist of an EAM integrated with a SOA.

Let M denote the number of RNs in the ring and assume, without loss of generality, that each RN connects the same number N of ONUs. In this case, Table 1 contains the number of optical devices that are required by each solution.

Table I
Number of optical devices as a function of M and N

DWC+UWC	**UWC only**	**TL-ONU**	**R-ONU**
$2M$ SOAs	M SOAs	$N{\cdot}M$ TLs	$N{\cdot}M$ SOAs
$2M + N{\cdot}M$ CWs	$M + N{\cdot}M$ CWs	$N{\cdot}M$ EAMs	$N{\cdot}M$ EAMs
$N{\cdot}M$ EAMs	$N{\cdot}M$ EAMs	$N{\cdot}M$ Rxs	$N{\cdot}M$ Rxs
$N{\cdot}M$ Rxs	$N{\cdot}M$ Rxs		

Since the same number of EAMs and Rxs is used in all solutions, the cost comparison only depends on the remaining devices. The cost thresholds that guarantee the WC-RN to be less expensive than the other alternatives are determined in the following.

The conditions for WC-RN with DWC+UWC and with UWC only to be less expensive than TL-ONU are then given by (1) and (2), respectively.

$$C_{SOA} < (N/2)\cdot C_{TL} - (N/2 + 1)\cdot C_{CW}; \qquad (1)$$
$$C_{SOA} < N\cdot C_{TL} - (N + 1)\cdot C_{CW,} \qquad (2)$$

where C_{SOA} denotes the cost of a SOA, C_{CW} the cost of a CW laser, and C_{TL} the cost of a TL. Since C_{CW} is typically much lower than C_{TL}, these conditions can be further simplified by neglecting C_{CW}, yielding the following approximations:

$$C_{SOA} < (N/2)\cdot C_{TL}; \quad (3)$$
$$C_{SOA} < N\cdot C_{TL}. \quad (4)$$

Figure 3 depicts the cost thresholds for which WC-RN is more economical than TL-ONU, as a function of N. The plot shows that if C_{SOA} is smaller than C_{TL}, the proposed architecture is always better than the use of tuneable transmitters at the ONUs (TL-ONU). In addition, it will still be better even when C_{SOA} exceeds C_{TL}, as long as the cost ratio C_{SOA}/C_{TL} is kept below $N/2$ when two WCs are used at the RN, or the same cost ratio is kept below N when a single WC is used at the RN.

When comparing the WC-RN and R-ONU solutions, the conditions for DWC+UWC and UWC only to be less expensive than R-ONU are given by expressions (5) and (6), respectively.

$$C_{SOA} > [(N+2)/(N-2)]\cdot C_{CW} \quad (5)$$
$$C_{SOA} > [(N+1)/(N-1)]\cdot C_{CW} \quad (6)$$

Figure 4 plots the cost thresholds above which WC-RN are more economical than the R-ONU approach. Since C_{SOA} is several times larger than C_{CW} and it is expected to remain so, the proposed solution using either one or two WCs is always better than using R-SOAs.

The relative cost thresholds derived above clearly suggest that, at current and expected cost ratios of optical devices like CW lasers, EAMs, SOAs, and TLs, the use of WCs at the RNs of the converged metro-access network is clearly more cost-effective than the alternative solutions using complex ONUs. In the proposed approach, the complexity/cost is kept in the RNs, which are significantly smaller in number than the ONUs. Moreover, and unlike both TL-ONU and R-ONU, the WC-RN approach enables the use of standard-compliant ONUs, guaranteeing backward compatibility with already deployed access systems.

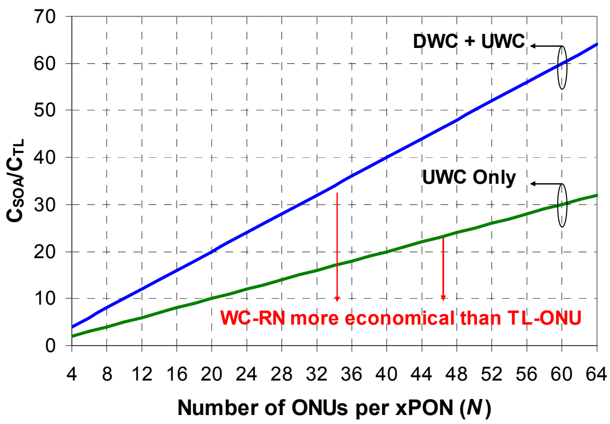

Fig. 3. Cost thresholds between WC-RN and TL-ONU.

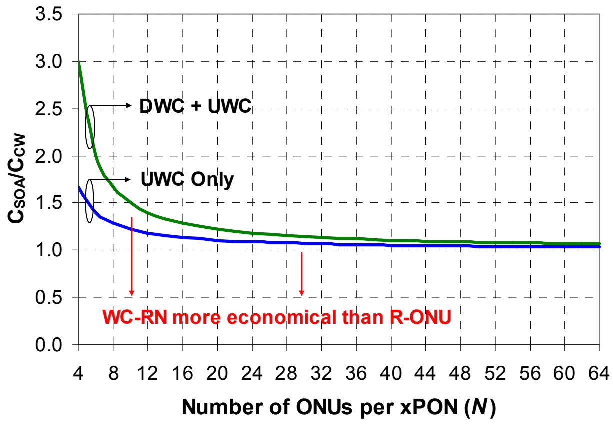

Fig. 4. Cost thresholds between WC-RN and R-ONU.

V. CONCLUSIONS

This paper presents a novel remote node architecture using all-optical wavelength conversion that is suitable for the convergence of metro and access networks, while at the same time guaranteeing backward compatibility with standard access systems and a single specification for the subscribers terminals. It also shows that, according to current and foreseeable prices of optical components, the envisioned system is more cost-effective than known alternatives targeting similar goals.

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