Considerations on Routing and Label Stacking in All-Optical Label Swapping Networks
(Invited)

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Abstract

Fast header processing in Optical Transport Networks (OTN) has been foreseen as one of the main challenges in All-Optical Packet Switched (AOPS) networks. The LASAGNE project aims at supporting All-Optical Label Swapping (AOLS), easing most of the header processing drawbacks in AOPS. However, AOLS is expensive mainly because each supported label requires the deployment of an All-Optical Logic Xor Gate (AOLXG).

The number of AOLXG required in a switch is equal to the number of the forwarded Label Swapped Paths (LSP). As a result, the overall number of AOLXG used in a network equals the number of hops used. Reducing the overall number of AOLXG implies selecting the shortest paths in the network. However, this leads to network bottlenecks. The trade-off between the number of AOLXG installed and maximum link utilization is thus manifest.

In this article, we study how labels can be stacked in order to reduce the overall number of AOLXG installed in the network. It is considered that a set of LSPs share a set of consecutive links (a path segment) in the network. The first (last) node of the path segment pushes (pops) one label in the stacks of the LSPs. Intermediate nodes in the path segment would regard only one label for all LSPs, reducing the number of AOLXG installed. The AOLS LASAGNE implementation is modified in order to propose an architecture able to stack labels all-optically.

In this paper we tackle the routing problem with the objective of reducing the number of installed AOLXG using label stacking. We show that if the number of labels is fixed, label stacking might routing solutions with less bottlenecks.

1 Introduction

The evolution of computer networks in the Internet has propelled Optical Transport Networks (OTN) in recent years. While the optical switching granularity has evolved from wavelengths to packets with very promising architectures, completely optical forwarding functions are still challenging ideals. In particular, although optical codification and transmission of information has been successfully performed, optical processing has been foreseen to be one of the main bottlenecks in OTNs [1].

With the recent deployment of All-Optical Flip-Flops (AOFF) and All-Optical Logical XOR Gates (AOLXG) technologies, optical processing is closer to become a reality nowadays [2] for All-Optical Packet Switching (AOPS). This optical processing is denoted as the name of All-Optical Label Swapping (AOLS) and it has its origins in the Generic MultiProtocol Label Switching (GMPLS) tag-switching mechanism. Although AOLS speeds up dramatically optical switching, it is expensive. The cost of deploying AOLS grows linearly with the number of AOLXG supporting labels (hence client connections) that the network is able to support [3]. Clearly, this raises a scalability problem.

The number of AOLXG in an optical node can be reduced if GMPLS label space reduction methods are considered. Namely, there are two methods for reducing the number of labels in GMPLS networks: *label merging* [4, 5] and *label staking* [6]. The reader is addressed to [7] for a brief study of the label merging applied to AOLS. Label stacking applied to AOLS is the main subject of analysis of this article.

This article is divided as follows. The second section summarizes a description of the LASAGNE architecture supporting AOLS. The third section proposes all-optical label stacking and discusses its benefits and drawbacks in an AOPS network. The last section presents the main conclusions of this article.

2 All-Optical Label Swapping

The LASAGNE project addresses the design of an all-optical label swapping (AOLS-block) device [2]. An AOLS-block is installed at wavelength ports in an AOPS requiring packets routing (see in Figure 1). An AOLS-block is in charge of reading the incoming label of a packet, replacing it by the proper outgoing label (label swapping) and converting the packet to its respective outgoing wavelength color.

An AOLS-block consists of the following four parts:

Optical Correlator Block. When a packet enters the AOLS-module, its label is separated from the payload at 40Gbs [8]. The optical label is fed to the *optical correlator* block. Within the *optical correlator* block, the incoming label is replicated several times, so every AOLXG [9] has a copy of the incoming label. An AOLXG is an optical device that a label with its complement and emits a high-intensity light pulse when they correspond to each other.

Local Address Generation Block. In order to perform the matching of the incoming label with the different recognizable labels of the switch, (the complement of) all these recognizably labels are generated in parallel by the *local address generation* block. This process takes place at the same time the incoming label is replicated.

Each of these local labels is given to a different AOLXG. Therefore, each AOLXG matches, in parallel, the same incoming label of the packet with a different locally "stored" label. Upon matching, the proper correlator transmits a high intensity light pulse. So far, the optical label has been identified. The high-intensity light pulse is sent to both the *new label generation* block and to the *control* block.

New Label Generation Block. The *new label generation* block produces the corresponding output label of the packet. This new label is inserted behind the payload.

Within the LASAGNE AOLS-block architecture, two label-generation blocks are needed: the *local address generation* block and the *new label generation* block. As mentioned before, the first one is in charge of generating the set of recognizable incoming labels, which feeds later the correlators. The second one is in charge of generating the set of outgoing labels. To generate a label (either incoming or outgoing), an Optical Delay Line (ODL) is used. An ODL is a very simple device comprised of several Fiber Delay Lines (FDL), couplers and splitters.

Control Block. The *control* block drives the wavelength converter, so the output packet (including the new label) can be tuned to its proper outgoing wavelength frequency. As a consequence, both the payload and the header are wavelength converted. The *control* block is implemented with AOFFs. Depending on the matching address (indicated by one of the pulses coming from the correlators), the appropriate flip-flop will emit a Continuous Wave (CW) signal at a certain wavelength. The frequency emitted by each AOFF is fixed. After the new label has been inserted, the packet is converted to the wavelength generated by the flip-flop.

Finally, the packet is routed by means of an AWG. Therefore, the wavelength on which the packet leaves the AOLS-block determines the outgoing port of the node. More details of the LASAGNE architecture can be found in [2].

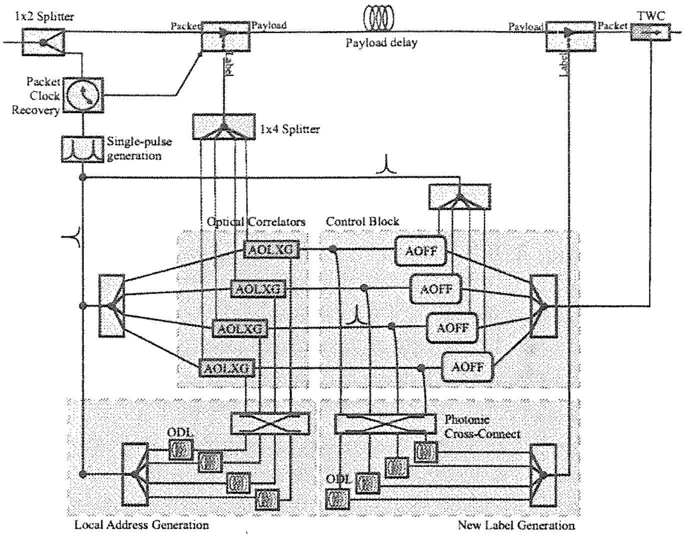


Figure 1: AOLS block able for label swapping

Two Photonic Cross-Connects (PXC) are used inside the AOLS-block to provide label swapping (inside the *new label generation* block) and wavelength conversion (inside the *local address generation* block) flexibility. The first PXC - in the *new label generation* block - switch the matching pulse from any AOLXG to any ODL. This offers a switching matrix between incoming (matching pulses) and outgoing labels (ODLs). The second PXC - in the *local address generation* block - switch the generated addresses between AOLXG correlators. This switching affects (by selecting) the fiber line through which the matching pulse is propagated. As a consequence, since each AOFF generates a CW fixed wavelength, the PXC selects the CW frequency generated by the AOFF fed by the matching pulse. These two PXCs are part of the network control plane and are low-speed dynamically configurable.

3 Extensions for All-Optical Label Stacking

In this section we analyze how *one additional label* can be stacked in the optical header, so the overall number of AOLXG used in the network is reduced. We propose a slight modification of the AOLS-block architecture in order to achieve this.

3.1 Implementation

Enabling an AOLS-block with both stacking and swapping implies that the system should be able to *a*) read only the top label of the header and, *b*) replace it by either none (pop), one (swap) or two (push) new labels depending on the incoming label.

The current implementation of the *Packet/Payload separation* circuit is able to extract only the top label of the packet, regardless of how many there are stacked. Therefore, the remaining label, if any, is treated as part of the payload. This would address issue *a*).

For issue *b*), AOLS stacking should be able to insert the two new labels before the packet. In the case of swapping, the system must behave as usual. The easiest way to provide two or one label insertion in the system is by allocating a fixed space for two labels, even though only one is placed sometimes.

Generating one or two labels can be implemented with a slight modification of the *new label generation block*, as seen in Figure 2.

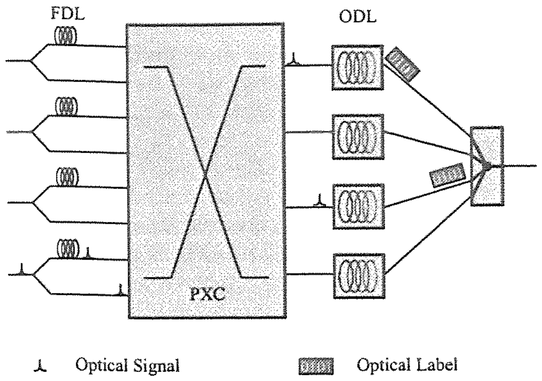


Figure 2: New Label Generation block allowing label stacking

The high-intensity pulse of the AOLXG that matched the incoming label is duplicated. One of the two pulses is delayed by an FDL for a fraction of time equal to the duration of one label. Both pulses are switched - one after the other due to the induced delay - using the PXC in order to generate two different labels. Both labels are generated out of each pulse using the same set of ODLs mentioned before. Finally, the labels are merged into one optical stream. Whether only one label is needed, the PXC should drop the pulse that was not delayed. In the event of popping the stack, the PXC should drop both pulses.

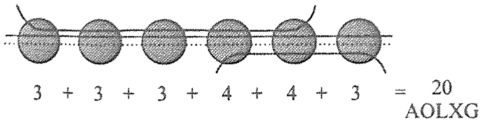
3.2 The Stacking Problem

To find the minimum number of AOLXG needed to route a set of paths (considering that one label can be pushed/popped) is not an easy task. There are two decisions problems that must be faced, which are going to be briefly discussed in this subsection.

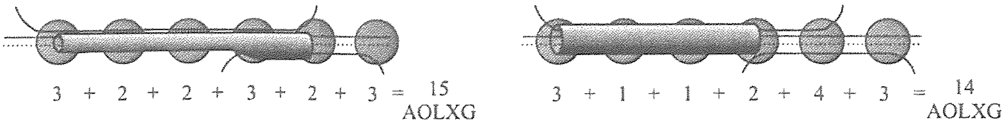
The first decision problem is where to *push* and where to *pop* the extra label. Consider the configuration shown in Figure 3a. This configuration has two feasible solutions which may be regarded in Figures 3b and 3c .

In this example, the first solution - shown in Figure 3b (suboptimal solution) - builds a "tunnel" that makes optical nodes in the network use a total of 15 AOLXG, while the second solution - shown in Figure 3c (optimal solution) - makes them use 14 AOLXG only.

The second decision problem that must be faced concerns which path-demands are going to be stacked by each tunnel. Consider that if *all* the possible path-demands (all those traversing the



(a) Paths and network configuration.



(b) Suboptimal solution.

(c) Optimal solution.

Figure 3: Stacking problem example.

last two links of the tunnel) are stacked, the creation of another tunnel using them is not allowed (one path-demand cannot be stacked inside two tunnels over the same links). This could avoid finding solutions using less AOLXG.

3.3 The Gain of Merging

Labels can be not only stacked, but merged as well. We proceed to discuss the benefit of using label merging solely, and then we refer to its combination with stacking.

As commented in [10], two Label Switched Paths (LSPs) in MPLS can be merged at certain Label Switched Router (LSR) if, and only if, they follow exactly the same route downstream the LSR. When two LSPs are merged, the same label is assigned in the path segment they have in common. Therefore, one label is allocated for both (or many more) LSPs, decreasing the number of labels that are needed. It is clear that this idea can be straightforwardly adopted to AOLS.

If the LSPs paths are given, determining how paths can be merged in order to obtain the least number of labels is a deterministic process. In other words, the minimum number of labels can be computed using a polynomial time algorithm, as explained in [11].

In the same way, when label stacking is considered, several tunnels can be merged together. As a consequence, the label space is reduced due not only stacking, but also merging.

Considering merging and stacking together, an stacking problem solution affects the number of AOLXG/labels that can be saved by merging as well. For instance, it could result in a better benefit to have 2 "mergeable" small tunnels, than two non-mergeable large ones.

3.4 Routing Considerations

As mentioned before, without any label space reduction method, the total number of installed AOLXG in a network is equal to the total number of hops needed. Therefore, the longer the paths are, the more AOLXG are needed in the entire network. This would imply that shortest-path algorithms (with all their disadvantages considering Traffic Engineering) would achieve the least expenditures concerning AOLXG.

When stacking is considered, a slightly longer route could result in an imperceptible lower QoS for the carried traffic, but in great savings for the cost of the network implementation. For instance, employing two long "stackable" routes may represent more savings than employing two "non-stackable" short ones. The overall number of used AOLXG of the connections, in the former solution, could be less than the two separate connections, in the later solution.

The ability of considering longer routes as adequate, as for cost expenditures, gives a broader fan of options for Traffic Engineering in AOPS. Therefore, the routing problem is henceforth considered together with the label space reduction problem as a means to analyze these trade-offs.

3.5 Modeling Considerations

As discussed by Van Caenegem *et al.* in [3], the dimensions of the AOLS-block architecture are intrinsically related to a) the number of incoming labels, b) the number of outgoing labels, and c) the number of bits used to code optical labels in the network. In concrete, concerning the AOLS-block dimensioning, we focus on the following metrics: total number of labels, length of the label, and maximum number of labels per node. The latest two are intrinsically related. As for routing *per se*, we focus on two metrics: maximum link utilization and hop count.

In order to compute the minimum number of labels using stacking, we proceed as follows. We assume that a traffic demand matrix and a network topology are given.

First, all paths in the network are generated. This is done using an exponential-time algorithm.

Second, a set of tunnels are generated. In fact, the same set of paths computed previously can act as the set of tunnels. However, this set can be reduced in order to have a better running time in further steps. A smaller set can be computed in polynomial time (see [12] for a proof) as it will be briefly mentioned. Every pair of paths is intersected. The intersections conformed by 2 or more links are considered as the *primary* feasible tunnel set. Then, the difference between any pair of primary feasible tunnels is computed. Those path segments resulting from the difference with more than 2 links conform the *secondary* feasible tunnel set. Both sets - the primary and the secondary tunnel sets - are the whole set of *feasible tunnels* to consider.

In parallel, we determine which of these paths can be merged together at every link using the algorithm proposed in [11]. As mentioned before, the running time of this last process is polynomial. Finally, the same process is applied for the set of feasible tunnels.

All this information is used by a path-based ILP model. Unfortunately, due the lack of space, the details on this ILP model are not given, but briefly explained instead. The ILP matches a tunnel with a path in such a way that a) only one tunnel is used for every path-link pair, b) the minimum number of labels is used.

Other functions, such as maximum number of labels per node and maximum link utilization, are considered as model constraints.

4 Simulation Results

The model is solved over a network of 9 optical nodes shown in Fig. 4. A set of random demands are generated as follows. A random number (generated uniformly between 0 and 10) of OC-1 demands is generated for every pair of nodes. In the same way, a random number of OC-3 and OC-12 demands (up to 6 and 2, respectively) are generated for every pair of nodes.

We fix the link capacity to the double of the minimum needed to route all demands (OC-246 per link, in this case), so there could be many routing solutions showing different trade-offs.

Initially, we route all demands without considering merging nor stacking. The routing solution with the minimum number of labels (implying in this case the least number of hops) is found. Similarly, the routing solution with the minimum maximum link utilization is found as well. Both are depicted in Table 1.

As it can be appreciated in the table, the gap between a routing solution achieving the minimum number of labels and the minimum maximum link utilization is small when no label space reduction is employed. In fact, the usage of 3 more labels (and 3 more hops) would imply a reduction of 1.3% in the utilization of the most congested link.

Obviously, the maximum link utilization cannot be reduced even more than that value. Therefore, we focus in how much it is increased when a label space reduction method is applied. For this, we solve the model with the objective of reducing the number of labels. The results are shown in Table 2.

The same minimum number of labels is reached, 72, in both cases. With merging, the price of reducing the number of labels by a 43.75% (from 128 to 72) is increasing both the number of hops and the maximum link utilization by 55.67% and 74.32%, respectively.

However, with stacking, the minimum number of labels can be obtained at a reduced price. In this case, the number of hops and the maximum link utilization are increased by 26.7% and 38.67% only, respectively.

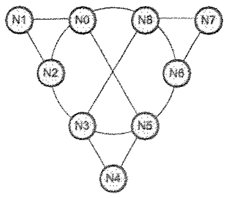


Figure 4: Simulation Network

	Min Hops	Min Max Link Util
Total Num. of Labels	128	131
Total Num. of Hops	970	973
Min Num of Labels per Node	21	22
Max Link Utilization	51.3%	50%

Table 1: Routing Solutions without Merging nor Stacking

	Merging	Stacking
Total Num. of Labels	72	
Total Num. of Hops	1510	1229
Min Num of Labels per Node	15	14
Max Link Utilization	89.43%	71.14%

Table 2: Routing Solutions when Merging or Stacking are employed

5 Conclusions and Future Studies

In this article label stacking applied to AOPS using AOLS is studied. The main motivation to use label merging in AOLS-based networks lays in the cost of supporting an optical label in the network.

The results show that by using the stack the label space can be reduced around 40%. The price of reducing the label space are seen in the routing, worse hop count and link utilization, however they outperform those obtained by label merging.

The simulations presented in this paper were focused on the extreme cases, i.e. the least number of labels that can be achieved and the minimum maximum utilization used. A more exhaustive study showing the rate between these two extremes is left for further studies.

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