Benefits of label stripping compared to label swapping from the point of node dimensioning

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Abstract All-Optical Label Swapping (AOLS) is a promising packet-switching technology to accomplish the gap between router forwarding speed and fibre transmission speed. The hardware requirements from the node however are unarguable a big disadvantage of these kinds of nodes. In this paper, we present two all-optical label switching nodes. One is based on the MPLS technology and one is an alternative switching strategy for packet-switching: label stripping. We compare both node architectures in terms of hardware requirements for different switching strategies and network parameters (such as topology and number of nodes).

Keywords All-optical networks · Packet-switching · Node dimensioning

Introduction

Despite the recent economic stagnation, the demand for telecommunication services continues to grow steadily. Even though this growth may have been over-enthusiastically acclaimed, it cannot be denied that

telecommunication networks are at the heart of our information-based economy and society. These networks nowadays are largely based on optical fibre technology. Indeed, the use of Wavelength Division Multiplexing (WDM) offers massive bandwidth through the parallel transmission of high bit rate channels onto the same fibre, at a very attractive cost per bit. Currently, we are witnessing the shift from purely point-to-point WDM systems to the introduction of real networking functionality at the optical level.

Automatically Switched Optical Networks (ASON) take the first step in that direction by enabling the automated set-up and tear-down of so-called lightpaths. Wavelengths are set-up between the endpoints in the WDM network. This avoids costly EO conversions in intermediate nodes but the resulting network is still relatively static and mandates efficient aggregation and grooming techniques. In this stage, this approach may be suitable for core networks where the traffic is highly aggregated and relatively predictable.

On the contrary, for networks carrying traffic of dissimilar protocols and bit rates, and therefore fluctuating heavily in both volume and time, traditional approaches do not offer sufficient flexibility. For networks that need to provide a large variety of service qualities in a highly dynamic environment, packet-switching can offer the flexible and bandwidth-efficient architecture that is called for. First optical packet-switched networks transported IP packets on an optical packet-by-packet basis but in order to make the routing decision in each intermediate node the whole IP packet was converted to the electrical domain. Despite the good bandwidth flexibility of this approach, the enormous amount of packet handling makes it badly scalable and moreover high-speed EO conversions are very costly. A more viable

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approach is Optical Packet-Switching (OPS), in which the packet payload remains in the optical domain while being switched in intermediate nodes. Even though the actual deployment of OPS in future high-performance networks is still questioned [1], compared to circuit-switched approaches it provides finer granularity to the optical layer.

Routing information (and other important information like Class of Service, CoS) is carried in the header of the packet. Although OPS allows optical bypassing of the transit nodes, the routing information must be consulted in each intermediate node to make the correct routing decision.

In the first approaches to OPS, the packet header has been separated from the packet payload and then converted to the electrical domain. In this case, the header is often modulated at a lower speed than the line speed, allowing for less costly EO conversions. In spite of this, OPS is still a challenge because of the high bit rates that force optical technology to switch very fast. To make routing decisions faster and more efficient the MPLS routing protocol [2] uses local labels that do not refer to a node-address in the network and are in front of the packet header. MPLS is a connection-oriented routing protocol in that before a packet is sent into the network, a virtual path (Label Switched Path, LSP) is set-up. This is in contrary to normal IP traffic, which has no predetermined path. More concrete, this means that the nodes through which the packet will pass are prepared to receive the packet and correctly forward it to the next node. In this way, the packet is forwarded hop-by-hop through the network.

Even though MPLS forms a good solution, it does not seem to cross the chasm between router switching speed (i.e. table look-up procedures still are time consuming) and fibre transmission speed. In an attempt to overcome this, research starts to focus on all-optical packet-switching by way of All-Optical Label Swapping (AOLS) [3–5].

All-Optical Label Swapping implements routing and packet-by-packet forwarding functions of MPLS directly at the optical domain. By using optical labels, the IP packets are directed through the optical network without passing them through electronics whenever a forwarding decision is necessary. Ideally, this approach has the ability to route packets/bursts independently of bit rate, packet format and packet length. With the help of MPLS labels the local look-up tables in routers are kept scalable and by using AOLs to make the table look-up procedure, packet forwarding is no longer a critical time-consuming activity. Still AOLs encounters new limitations in making the forwarding decisions. The lack of all-optical memory makes AOLs nodes very com-

plex and resource consuming. MPLS requires a look-up table in which the forwarding information for all LSPs passing the node is stored. In the all-optical node design proposed in the LASAGNE project (AOLS employing optical logic Gates in Network nodes) [6–7], this memory absence has been overcome by installing a label comparator and just-in-time label generation. Since light keeps on running, thus requiring on-the-fly label swapping, and the design of those all-optical components is specified to a particular label, there is no possibility in reusing an all-optical component for different labels. Whereas the electronically implemented look-up table was easily to adapt to changing routing demands (i.e. LSPs are set-up, torn down at all possible moments in the network), the number of all-optical components and how they are designed will be directly related to the dimensions of the routers (and thus the ability to accept more or fewer LSPs).

The work presented in this paper discusses the number of labels needed in a network to establish all the possible LSPs between all the nodes in the network. Four alternative label swapping strategies and a newly proposed label stripping strategy are described in detail in the sections below. The label swapping strategies are based on the MPLS principle, but all of them are labeling the LSPs in a different way. By using other (implicit) routing information, it will be possible to reduce the number of different labels in the network. However, the number of LSPs passing the node stays the same. Together with a reduction of the number of labels (or components), we are also targeting to reduce the label length and thus the complexity of individual components. To find out which switching strategy is most suitable for the Lasagne node, a comparison of these strategies in terms of number of bits in the label and the dimensional requirements for a Lasagne node is carried out. Once the individual node is characterized, it is of great importance for the completeness of this study to map the network influences on the node dimensions and label length, too. For that purpose, we will also work out the influence of different network parameters such as number of nodes, degree of meshing and label stacking.

The remainder of this paper is organized as follows: the subsequent Section “Node design” will outline the Lasagne node architecture and the dimensioning indicators. The different label swapping strategies will be addressed in Section “Switching strategies”. After describing our research approach in Section “Approach and methodology of the dimensioning study”, they will be compared and discussed in terms of dimensions in Section “Results”. All conclusions will be summarized in the final Section “Conclusion”.

Fig. 1 LASAGNE node
(photonic router)

Node design

Figure 1 shows the AOLS node-architecture proposed by the Lasagne project. The main functionalities such as label reading, label insertion and packet routing are based on the use of all-optical logic gates [8–11]. These functionalities are performed by the AOLS-block (Fig. 2) [12–17], for which we have investigated its resource requirements under the different switching strategies as described in Section “Switching strategies”.

The wavelengths entering the node are demultiplexed and for each wavelength an AOLS-block is implemented. Each AOLS-block comprehends the true forwarding functionality of the incoming packets. Entering the AOLS-module, the packet payload is separated at 40 Gbit/s [12]. The extracted optical label is fed to a bank of XOR autocorrelators [13], where the comparison between the label and a set of local addresses is performed. These local addresses are generated using a network of optical delay lines (ODLs). An ODL is comprised of a set of interconnected fibre delay lines, couplers and splitters, generating a bit sequence out of one pulse. Thus, comparing the incoming label to the local addresses implies that for each possible incoming label a separate ODL and a correlator have to be installed in the AOLS-block. After comparison, a high intensity pulse will appear at the output of the XOR correlator with the matching address. This pulse feeds a control-block that drives a wavelength converter. The control-block is made up of optical flip-flops [14]. Depending on the matching address (correlator output pulse), the appro-

priate flip-flop will emit a Continuous Wave (CW) signal at a certain wavelength. In this way, the internal wavelength is chosen. Meanwhile a new label is generated in the appropriate ODL. The new label is inserted in front of the payload and both the payload and the new label are now converted to the wavelength defined by the flip-flop [17]. The packet is then sent through an AWG. Thus, the wavelength on which the packet leaves the AOLS-block determines the outgoing port on which the packet leaves the node. Two switches provide the flexibility to assign different outgoing labels and wavelengths to the same incoming label. From the AWG, packets go to the contention resolution block that belongs to their output-port. This module provides the flexibility to overcome the problems of contention in the network.

From the description of the node, it may be clear that the more labels an AOLS-block has to distinguish, the more components need to be installed. All-optical label recognition seems not to be very well scalable and the use of AOLS swapping in an OPS network creates some challenges and opportunities from the networking point of view. To lower the cost of the AOLS-node, it is beneficial to reduce the number of different labels used throughout the network and hence the number of bits occupied by the label. For that purpose, we investigated different label switching strategies concerning their resource requirements for the AOLS-blocks to be installed.

Reduction of the number of labels not only lies within the switching strategy. Even though it is very important to choose the appropriate label distribution also the

Fig. 2 Detailed LASAGNE all-optical label swapper

network topology and possibility to stack the labels have a hand in the label length (Well over thought choices can limit the label length to 2 or 3 bits, thus only installing 4 or 8 correlators in one AOLS-block).

Switching strategies

A switching strategy defines the way the packet labeling is done. Which and how many labels will be used depend on which routing information is used to make routing decisions and to distinguish between LSPs.

The dimensions of the AOLS-block, as described in Section “Node design”, are subject to the switching strategy used throughout the network. The proposed switching strategies can be subdivided in two categories: label swapping and label stripping. In the label swapping strategies, an old label is replaced by a new label in each node.

This is in contrary to the label stripping strategy, where the label is comprised of a set of concatenated small labels, one for each intermediate node on the LSP of the packet. In the remainder of this paper, we will speak about using and reusing labels. To use the same set of labels indicates that the same label value refers always

to the same LSP, wherever it is used. For instance, two wavelengths using the same set of labels implies that label 1 used on the first wavelength (λ_1) refers to the same LSP as label 1 used on the second wavelength (λ_2). Reusing the labels indicates that labels have a different meaning on different LSP-carriers. For instance, two wavelengths reusing the same set of labels means that label 1 on wavelength λ_1 refers to a different LSP than label 1 on wavelength (λ_2). In the remainder of this section, we first discuss the different label swapping strategies. We end with addressing the newly proposed label stripping switching strategy.

Label swapping

We assume that label sets start counting at 0. To visualize the label distribution we use wavelength–fibre port matrices based on Fig. 3. One fibre port contains all wavelengths in one row of the matrix. One wavelength colour contains all wavelengths in one column of the matrix. All wavelength arrows pointing to the same label set use this same label set. Since we assume that label sets start their counting at 0, drawing different label sets actually implies a reuse of the labels of one set.

Fig. 3 Wavelength-fibre matrix containing all wavelengths and fibres incoming in the node. One column contains all wavelengths with the same colour in the node. One row contains all wavelengths within one fibre port

To address the dimensioning study we use the parameters from Table 1. Their denotation will become clear in the line of this paper. Some of them are already used to describe the labelling strategies.

Label swapping strategy 1

In the “input Label is output Label plus output fibre port (no reuse)” routing strategy, every possible LSP passing through a node in the network has a label, different from the other LSPs trough that node. This implies that every wavelength needs to be able to recognize all the possible incoming labels. Forwarding implies according to Table 2 that based on the incoming label we replace the label and make the choice for the appropriate output-port. In what follows, we will name this labelling strategy as No Reuse. For a visualization, we refer to Fig. 4. The label set size is defined by the sum of all the wavelengths entering the node through all possible fibre ports.

Table 2 Look-up table for No Reuse

Input label	Output fibre port	Output label
5	3	3
2	2	8

Fig. 4 Building of the label set for the strategy No Reuse. All wavelengths pointing through the same bar use labels from the same label set

Label swapping strategy 2

The “input label plus input wavelength is output label plus output fibre port plus output wavelength” routing strategy is similar to the previous one. In this case, a LSP is defined by its label and the wavelength it is on. This implies that labels can be reused on different wavelengths within one port, but the wavelength cannot be used for contention resolution. Contention occurs when two packets are competing for the same wavelength in the same fibre port. If we could choose the

Table 1 Dimensioning parameters

Name	Description
N	Number of nodes in the network
$n = 1 \dots N$	Node Index: Refers to the node
P_n	Number of ports per node n
$p = 1 \dots P_n$	Port Index: Refers to the port within a node
W_{pn}	Number of wavelengths per port p from node n
$\lambda = 1 \dots W_{pn}$	Wavelength Index: Refers to the wavelength within a port
$LSP_{p\lambda n}$	Total number of LSPs on wavelength λ in port p
l	Bit length in metre (e.g. bit rate 40 Gbit/s and speed of light $2 \cdot 10^8$ m/s giving $l = 5$ mm per bit)
B	Number of bits per label
$Neigh_{n^*}$	The neighbour nodes of node n^* . This is a set of couples (p, n) referring to the node number and the number of the port through which it is connected to n^*
p^*	Port number of AOLS-block under calculation
λ^*	Wavelength number of AOLS-block under calculation
n^*	Node number of AOLS-block under calculation

Table 3 Look-up table for Label plus Wavelength is Label plus Port plus Wavelength

Input wavelength	Input label	Output fibre port	Output label	Output wavelength
λ_1	5	3	3	λ_7
λ_4	5	2	8	λ_{12}

wavelength on which to put the packets, it is possible to avoid buffering. This is a tricky task in optical networks because of the lack of mature optical buffers. In case wavelengths are used to solve contention resolution, the wavelength a packet is on is then not important for the routing. For the swapping strategy, the wavelength carries implicit routing information. This, for correct forwarding the packet needs to be put on the specified wavelength and the wavelength is not used for contention resolution (Table 3).

To make the dimensioning study we will define wavelength colours. Per fibre port different coloured wavelengths enter the node. In this strategy it is impossible to use the same label for a LSP on wavelength λ_1 in port 1 and another LSP on wavelength λ_1 in port 2. Although it is possible to use the same label for two different LSPs, for which the first is on wavelength λ_1 (no matter what port) and the second on wavelength λ_2 (no matter what fibre port). Thus, colour will be a set of wavelengths (each wavelength in the set belongs to another fibre port) using the same labels. The use of colours is visualized in Fig. 5. All wavelengths in one column use the labels from the same set to distinguish between their LSPs. There are as much columns as the number of wavelengths in the largest fibre port ($=\text{Max}_p(W_{pn*})$). The size of a label set is thus defined by the sum over all LSPs belonging to the same colour.

Label swapping strategy 3

The “input label plus input fibre port is output label plus output fibre port” routing strategy defines the LSP by its label and the fibre port on which it is entering a node.

Fig. 5 Building of the label sets while using wavelength information as implicit routing information. This is the use of colours. All wavelengths pointing through the same bar use labels from the same label set

On the node level an AOLS-block only needs to recognize the labels of the LSPs that come through the port the wavelength belongs to. The set of labels is thus used by the wavelengths within one fibre port but reusable for different ports. This is visualized in Fig. 6, all wavelengths belonging to the same fibre port form one row of the wavelength-fibre port matrix. Thus, the size of one label set comprises the labels for all LSPs carried by the wavelengths in a row of the matrix (Table 4).

Label swapping strategy 4

The last, “input label plus input fibre port plus input wavelength is output label plus output fibre port plus output wavelength” label swapping strategy is similar to the previous one. In this case also the wavelength, on which a LSP is, is important. This implies again that wavelengths are not used for contention resolution. The labels are reusable per wavelength and per fibre port as is visualized in Fig. 7. The size of a label set is in this case limited to the number of LSPs a particular wavelength carries (Table 5).

Label stripping

In this section, a new label switching strategy is described. In Fig. 8, a packet is switched through the network based on an end-to-end label. This label is a concatenation of multiple local labels. In each intermediate node, the AOLS-block strips off the first bits of the end-to-end label (this is the local label) and makes a switching decision. We explain the principle of label stripping using Fig. 8. A packet enters the all-optical

Fig. 6 Building of the label sets while using the port number as implicit routing information. All wavelengths pointing through the same bar use labels from the same label set

Table 4 Label plus port is label plus port

Input fibre port	Input label	Output fibre port	Output label
1	5	3	3
1	6	3	4
3	5	2	8

Fig. 7 Building of the label sets while using the fibre port number and the wavelength as implicit routing information. All wavelengths pointing through the same bar use labels from the same label set

network through the router A. It gets the label Drop-E-D-C, and is sent on the link AB. The router B strips off the first label, which is label C. From the content of this label, router B knows the packet has to be sent on the link that connects B to C. The remaining packet label is now Drop-E-D. In routers C and D the packet goes through the same procedure. In router E the label content is DROP. That means the packet has to be dropped from the all-optical network. However we are not replacing this local label, there is a possibility to work

with fixed length headers by an internal shifting of the local labels inside the header. The remaining local labels in the end-to-end label are shifted to the beginning of the packet. This increases the label-free space between the packet payload and the packet header. The strategy makes use of the different wavelengths for contention resolution.

Figure 9 gives the node architecture adapted to label stripping. We do not need a new label generation and a second switch. The packet enters the label stripping

Table 5 Look-up table for Label plus port plus wavelength is label plus port plus wavelength

Input fibre port	Input wavelength	Input label	Output fibre port	Output wavelength	Output label
1	λ_1	5	3	λ_7	3
1	λ_3	5	4	λ_4	7
3	λ_1	2	2	λ_{12}	8
3	λ_3	4	2	λ_{12}	7

Fig. 8 Label stripping principle **Fig. 9** Label stripping block architecture

block at the upper left corner, and just as for label swapping the label and payload are separated. The content of the label is compared by the installed AOLXG's and a routing decision is taken by selection of the right internal wavelength (the match pulse of one of the AOLXG activates one of the all-optical flip-flops). The routing information carried by the local label is the port number to which the packet has to be switched in the particular intermediate node. That is why we distinguish a sepa-

rated local label for each intermediate node on the LSP of the packet.

Approach and methodology of the dimensioning study

This section describes the choices made to accomplish the dimensioning study. We start with a description of the considerations made while dimensioning the input/

Fig. 10 Dimensioning possibilities of the output stage of an AOLS-block

output stages of the AOLS-block, followed by a detailed description of the measures to count the AOLS-resources.

Methodology

To accomplish the study of mapping the AOLS-block resource requirements, we calculated the shortest path based on the algorithm of Dijkstra between each node pair from the network under study. From those data it is possible to extract how many LSPs are passing a node. Combining this with the traffic pattern proposed in [18], it is possible to estimate the number of LSPs per wavelength, per node, per fibre port, according to the wavelength capacity. Following the MPLS principle, LSPs are getting a unique label. But according to the switching strategy used, there is a possibility in reusing the same set of labels (discussed in the previous section). Following these, the number of LSPs reusing the same set of labels is defined and from this number the number of labels and the label length is derived. The dimensions of the input-stage are defined by size of the label set used by the LSPs entering the node on a link (wavelength/fibre port, according to the swapping strategy). An input-stage thus clearly only has to distinguish between the labels of one label set.

The dimensioning of the outgoing stage is completely defined by the dimensions of the incoming ports¹ in the neighbour nodes of node n^* . This is due to the protocol that is assigning the labels during the packet's LSP set-up. This protocol works from destination to source. Once

the destination is aware of a coming packet stream, the intermediate nodes are informed. Each following node in the path informs the former node of the label with which it expects the packet to arrive. For that the former node should be able to swap the incoming label into the label requested by the following node. (e.g. The destination informs the last but one node, and so on, ..., to the source). since the former node should be able to swap the incoming label into the correct new label the dimensions of the output stage of the former node are defined by the dimensions of the input stages of all incoming ports in its neighbour nodes it is connected to.

In Fig. 10 on the left the AOLS-blocks of the node n^* are depicted. There is one AOLS-block per wavelength, thus one AOLS-block per combination $p^* = 1 \dots P_{n^*}$ and $\lambda^* = 1 \dots W_{p^*n^*}$ (Assume the total number is v , in the figure only AOLS-block 1 and v are depicted). An LSP entering an AOLS-block can be sent to every possible neighbour through one of the outgoing ports (assumed there are L ports). For that we can interpret the incoming label set as compound of subsets. Talking about the first AOLS-block, each subset (k_{1p}) stands for the number of labels (packets) that are sent to the output port (port = $1 \dots L$). We can make this subdivision for each of the AOLS-blocks. In that way, the total number of LSPs on the outgoing links ($= K_{\text{port}}$ with port = $1 \dots L$) is composed of the sum of LSPs from the different AOLS-blocks ($= \sum_{i=1}^v k_{i1}$, in case of the first output port). The size of the incoming label set of the next node is thus directly defined. To dimension the outgoing label set of the next node two alternatives are possible.

(1) Since the incoming label set of the node is subdivided in several smaller sets, and assumed that the

¹ For the generality of the discussion we will use 'port' to address the links to the node's neighbours. Dependent on the label swapping strategy the port will be a fibre or wavelength port.

counting of the label set starts by 0 (assumption made in Section “Label swapping”) the outgoing label set of AOLS-block 1 can be dimensioned as $\text{Max}(\text{port} = 1 \dots L : k_{\text{port}})$. In this way, each label of the biggest subset can be swapped in a unique label. This is necessary to distinguish between the LSPs. But the former does not take into account that there are more LSPs on the outgoing link than only these of the AOLS-block 1. For instance, an error occurs when the label assigning protocol wants to assign the label 10 to an LSP coming from AOLS-block 1, if the outgoing label set $\text{Max}(\text{port} = 1 \dots L : k_{\text{port}})$ only comprises 8 labels (0..7). This is a real danger because (as previously said) the outgoing label is defined by the value requested by the next node. For that reason, dimensioning alternative 2) is a better option.

(2) To overcome the latter problem, each AOLS-block should have the possibility to swap labels into every possible label used on one of the outgoing links. Since the assumption is made that the label set start counting at 0, we may assume that the largest incoming label set of a neighbour port will comprise all those possible labels. This results in a dimensioning of the outgoing label set as:

$$\begin{aligned} & \text{Max}[\text{port} = 1 \dots L : K_{\text{port}}] \\ &= \text{Max} \left[\text{port} = 1 \dots L : \sum_{i=1}^v k_{i\text{port}} \right] \end{aligned}$$

In the former discussion on the dimensioning of the output stage we did not specify the port. According to the label swapping strategy, this could be a fibre port (in case of No Reuse and Label + Port) or a wavelength port (in case of Label + Wavelength and Label + Wavelength + Port). The detailed dimensioning of the output stage for each label swapping strategy can be found in Table 8.

To make a feasible comparison, we extracted dimension indicators from the AOLS-block design. To make a conveniently arranged dimensioning study, we have subdivided the AOLS-block into two parts, the input-stage and the output-stage. The input-stage comprises all dimension indicators associated with the incoming labels, which have to be read. The output-stage then exists of the optical components to form the new labels. To address the dimensioning study we have used the parameters in Table 1. Each AOLS-block can be uniquely dimensioned. A particular AOLS-block is completely defined by the node, fibre port and wavelength and thus the dimensions of all AOLS-blocks installed in the node can be different.

INPUT stage AOLS-block

- Incoming ODLs: The number of ODLs needed to generate the local addresses to which the incoming label has to be compared.
- Length: The total Length of the incoming ODLs (sum of the ODLs multiplied by their respective length), in metre. This measure reflects the complexity of the ODLs to be installed. The longer they are, the more complex they will be.
- Correlators: The number of correlators needed to make the appropriate comparisons of the incoming label and the local generated addresses per node/port, but definitely per wavelength.
- Switch I: The switches implemented to connect the local addresses to the appropriate flipflops. These could be installed per port/wavelength/node.
- Bits: The number of bits in a label. This measure reflects the complexity of the correlators to be installed (Tables 6 and 7).
- The number of flipflops necessary to address all internal wavelengths defines partly the size of switch I. We assume it is the same for each switching strategy. It is represented by FF in the tables.

OUTPUT stage AOLS-block (this does not exist in label stripping nodes)

- Outgoing ODLs: The number of ODLs needed to generate the new labels. Since we assume all label sets start counting at label value 0 and we use the dimensioning strategy from Fig. 10, situation B, the output stage is well dimensioned when taking the biggest possible incoming label set of all neighbours of the node.
- Length: The total length of the Outgoing ODLs (sum of the ODLs multiplied by their respective length), in metre. This measure reflects to the complexity of the ODLs to be installed. The longer they are, the more complex they will be.
- Switch II: The switches implemented to connect the pulse from the matching correlator to the appropriate outgoing ODL to generate the new label (Tables 8 and 9).

Results

The dimensioning impacts of the label switching strategies on the AOLS-block resource requirements are

Table 6 Number of incoming ODLs per AOLS-block INPUT stage per switching strategy resources per AOLS-block INPUT stage

	Number of incoming ODLs (= Inc)
No Reuse	$\sum_{p=1}^{P_{n^*}} \sum_{\lambda=1}^{W_{pn^*}} \text{LSP}_{p\lambda n^*}$
Label + Port	$\sum_{\lambda=1}^{W_{p^* n^*}} \text{LSP}_{p^* \lambda n^*}$
Label + Wavelength + Port	$\text{LSP}_{p^* \lambda^* n^*}$
Label + Wavelength	$\sum_{p=1}^{P_{n^*}} \text{LSP}_{p\lambda^* n^*}$
Label Stripping	P_{n^*}

Table 7 Resources per AOLS-block INPUT stage

Number of incoming ODLs	Inc
Number of bits	$\log_2 (\text{Inc})$
ODL Length	$(\text{Inc}) \cdot \log_2 (\text{Inc}) /$
Number of correlators	Inc
Switch I	Inc. FF

best described by a case study. In this section we will first describe the example-network and example-traffic. Further on we make a comparison of the different label switching strategies and to close this section. We investigate the AOLS dimensions when changing some network parameters (topology, number of nodes and hierarchy).

Case study

To assess the resource requirements of AOLS-blocks, we investigated the impact of the labelling strategies on the Backbone European Network (Fig. 11) and the demand proposed in [18]. Different network topologies are created by removing/adding nodes/links from/to the

Table 9 Resources per AOLS-block OUTPUT stage

	Resources per AOLS- block OUTPUT stage
Number of outgoing ODLs	Out
Length	$\text{Out} \cdot \log_2 (\text{Out}) /$
Switch II	Out.Inc

Fig. 11 Basic European network

network. This is done in order to make the dimensioning calculations for several types of networks.

Label stripping versus label swapping

Section “Switching strategies” described five different label switching strategies. According to their properties they either use the wavelength domain for contention

Table 8 Number of outgoing ODLs per AOLS-block OUTPUT stage per switching strategy

	Number of outgoing ODLs (=Out) = $\text{Max} \left[\text{port} = 1 \dots L : K_{\text{port}} \right]$
No Reuse	$\text{Max} \left((p, n) \in \text{Neigh}_{n^*} : \sum_{k=1}^{P_n} \sum_{\lambda=1}^{W_{kn}} \text{LSP}_{k\lambda n} \right)$
port Label + Port	$\text{Max} \left((p, n) \in \text{Neigh}_{n^*} : \sum_{\lambda=1}^{W_{pn}} \text{LSP}_{p\lambda n} \right)$
Label + Wavelength + Port	$\text{Max} \left((p, n) \in \text{Neigh}_{n^*}, \lambda = 1 \dots W_{pn} : \text{LSP}_{p\lambda n} \right)^a$
Label + Wavelength	$\text{Max} \left((p, n) \in \text{Neigh}_{n^*}, \lambda = 1 \dots W_{pn} : \sum_{k=1}^{P_n} \text{LSP}_{k\lambda n} \right)^b$

^a The number of neighbour ports is now defined by the number of fibre ports the node n^* is connected to and inside these fibre ports the number of wavelengths

^b The number of neighbour ports is now defined by the number of colours the node n^* is connected to. A colour is formed by wavelengths from different fibre ports, for that we take the maximum over the sum of those wavelengths

resolution or not, they use the port numbers as extra routing information, and they have more or less label overhead. In this section, we will compare those switching strategies with each other in order to define the influence of the above mentioned properties to the dimensions of the AOLS-block.

Wavelength used for contention resolution

In two swapping strategies, wavelengths are used for contention resolution. In the following, those swapping strategies are compared to the according strategy that is not using wavelengths for contention resolution. Contention resolution avoids the need of buffering. This is very important in optical networks because of the lack of mature optical buffers. As seen from Fig. 12 avoiding buffering by contention resolution based on wavelengths has its implications on the dimensioning of the AOLS-blocks. Using wavelengths for contention resolution permits to spreading the demand of one LSP over the capacity of different wavelengths using the same label. This prevents the reuse of the labels on different wavelengths for different LSPs and thus more different labels are needed to forward the same number of LSPs (see number of Correlators in Fig. 12). Together with an increasing number of labels, the number of bits to form one label increases (theoretically all LSPs can appear on one wavelength) so not only the number of components increases, but also the component itself requires more resources. The resource reduction has most impact on the input stage of the AOLS-block. This is because an output stage is dimensioned as a Max(neighbour input stages), thus always the upper bound is taken into account.

Using the fibre port as extra routing information

To measure the impact of the incoming port carrying routing information we take the results of the swapping strategies where the incoming port is used as routing information and divide them by the results of similar strategies where it is not.

We could expect that the dimensions would be smaller in case the incoming port is used as routing information because this permits the same label set to be reused on different wavelengths, belonging to different ports. This is exactly what can be seen from Fig. 13.

Label overhead

Although the local labels in the stripping strategy are short, the label to be transported (end-to-end label) can be longer than in the label swapping strategies. This is because in the former the end-to-end label is

a concatenation of local labels. Actually there is no much overhead difference between the swapping strategy and the stripping in case only the label-field is duplicated in the latter strategy. Assume the header requires a label-field (comprises the forwarding information), guard bands (to separate the different information fields) and CoS-field (CoS: to indicate the traffic priority). If in the label stripping case, the CoS-field is reused by the intermediate nodes, only the label-field and the total number of guard band bits will be longer compared to the swapping strategy (see Fig. 14). On the other hand if we should duplicate the whole header (label + guard bands + CoS) for each intermediate node, then the overhead will become more significant. Table 10 gives an overview of the label overhead introduced by the different switching strategies. It is important to review the overhead not only for individual payload lengths, but also taking into account the relative payload length distribution of packets in the network. Table 10 indicates that the overhead introduced by the label stripping strategy worst case is only four times bigger than the one for label swapping under a payload distribution of 50%, 37.5%, and 12.5% for 40, 520 and 1,500 bytes payloads.

Comparison between the best label swapping approach and label stripping

From the above discussion, it is clear that the most optimal swapping strategy concerning the label length and dimensions of the AOLS-block, is to use the wavelength as well as the port for extra routing information. As already several times mentioned, the main drawback of this swapping approach is the inability of using the wavelengths for contention resolution. In this section we compare this strategy with label stripping. Although the swapping strategy is the best performing compared to all the other swapping strategies in terms of dimensions and label length, it does not seem to come near to the label stripping's resource requirement performance (Fig. 15). In the figure below, we also have compared the label + port swapping strategy with label stripping because the use of wavelengths for contention resolution is an important networking feature.

Influences on the dimensions from the network point of view

This section will address the dimensions of the AOLS-block while influenced by other parameters than the switching strategies. We will have a closer look at the influence of the network topology, the number of nodes in the network and the possibility of providing label

Fig. 12 Dimensioning ratio (no contention resolution)/(contention resolution). Values represent the comparison of the requirements of the biggest nodes in the network

Fig. 13 Dimensioning ratio (Port as routing info)/(Port not as routing info). Values represent the comparison of the requirements of the biggest nodes in the network

	Guard Bands	Cos-field	Label-field	Total
Swapping	3 x 3 bits	1 x 3 bits	1 x 8 bits	20 bits
Stripping (CoS reused)	10 x 3 bits	1 x 3 bits	8 x 3 bits	57 bits
Stripping (fully replaced)	17 x 3 bits	8 x 3 bits	8 x 3 bits	99 bits

Fig. 14 Header length for the different switching strategies

stacking. When comparing the number of bits in a label we do not take into account the number of guard band bits, neither the total length of the end-to-end label in case of label stripping.

Network topology

Starting from the routing algorithm, a more meshed network implies fewer LSPs on the different links, thus fewer LSPs enter a node through the same fibre port, and thus fewer labels are needed. Fewer labels imply fewer bits. On the other hand less bandwidth per link is needed,

causing fewer wavelengths entering a node. Our calculations show that although the node is connected to more neighbours, and the number of LSPs crossing the node is less in a more meshed network, the number of LSPs per wavelength remains the same resulting in a fewer total number of wavelengths needed to accomplish the LSP's bandwidth need. This is what we can see from Table 11. When only the fibre port (Label + Port) is used as implicit routing information there is a gain in the number of bits of a label. After all, a more meshed network has more fibre ports and thus, if a distinction is made between them, more routing information can be extracted

Fig. 15 Resource requirements, label swapping compared to label stripping. Values represent the comparison of the requirements of the biggest nodes in the network

from them. When only the wavelength is used as implicit routing information (Label + Wavelength), we foresee that because a more meshed network carries the same number of LSPs per wavelength, there will be no bit gain from using wavelengths as routing information (see also Table 11). In other words: in the Label + Wavelength case wavelengths belong to a colour. A colour is (as assumed in Section “Switching strategies”) made up of wavelengths from different fibre ports. If the network is more meshed this implies each node has more fibre ports, implying that more wavelengths and thus more LSPs are brought together into one colour thus more labels are needed causing the label length to increase. On the other hand, the number of colours in a more meshed network decreases (because one fibre port carries fewer wavelengths, see begin of this section). In case both the wavelength and the fibre port are used as implicit routing information (Label + Port + Wavelength) we would foresee that the label length would stay the same. After all, the number of LSPs per wavelength stays the same. But, from Table 11 we see that for a more meshed

network the number of bits in a label increases. We can explain this by going back to the routing algorithm that is used to calculate the shortest paths for the LSPs. We are using the shortest path algorithm of Dijkstra. Since there are fewer links in a ring network, the paths will be longer and more LSPs will use the same link. As a matter of course more wavelengths will be needed to carry all the data information. Since we are using the wavelength as routing information, a fixed wavelength per link is assigned to a LSP. In Table 11 we used the maximum number of bits that is needed on the different links. On one of the links in the mesh network we find 19 LSPs but only one wavelength. These small bandwidth LSPs cause the wavelength to need 19 labels (=5 bit). In the ring network, even more LSPs and more wavelengths are found on the same link. In that case, a bandwidth expensive LSP goes together with a bandwidth cheap LSP to fill one wavelength. This causes one wavelength only to need 2-bit labels. In case of No Reuse the label length seems independent of the network’s degree of meshing. However a fewer number of LSPs crosses the

Table 10 Header length for the different switching strategies

Relative distribution of the packets		size (bytes)	payload		
			40	520	1500
			50,0%	37,5%	12,5%
		header (bytes)	overhead		
Stripping	Swapping	2,5	5,88%	0,48%	0,17%
	CoS reused	7,125	15,12%	1,35%	0,47%
	fully replaced	12,375	23,63%	2,32%	0,82%

3,14%
8,13%
12,79%

Table 11 Difference in the maximum number of bits per label for a ring network, and more meshed network

#Bits per label	No Reuse	Label + Wavelength	Label + Port	Label + Port + Wavelength	Stripping
Ring	8	3	7	2	2
Mesh	8	6	6	5	3

node in a mesh network, there is no reduction with a factor two (that is needed to see a label length reduction with one bit), so the label set size reduction is invisible in the label length.

What concerns the label stripping case, a more meshed network causes the labels to be longer. This is obvious because the length of a local label depends on the number of fibre ports in a node. But more meshed networks implies shorter routing paths. The end-to-end label length changes from 18 bits (9 hops * 2 bits) for the ring network to 21 bits (7 hops * 3 bits) for a meshed network.

Similar conclusions as for the number of bits can be drawn from Fig. 16, which is representing the number of correlators in one AOLS-block in the node. Although the No Reuse approach requires 8 label bits for both the Ring and the Mesh network we now see in Fig. 16 that meshing the network has a good effect on the node dimensions. Also for the other strategies this counts: although each extra bit in a label can imply a doubling of the number of correlators to be installed, we do not need to double the number of correlators and install the maximum per AOLS-block. Thus, the effect of an increasing number of bits is flattened out in the number of correlators. A strongly meshed network thus will contribute to the scalability of the AOLS-blocks in the network.

Number of nodes

It is needless to say that for the label swapping case, the number of bits in the label increases when the number of nodes increases. We see (in Fig. 17) an increase from 7 to 9 if the number of nodes changes from 16 to 28 for the No Reuse case. A bigger number of nodes indeed implies a bigger number of LSPs to be set up and thus more labels needed and those will be longer.

For the label stripping case the local label remains the same length. This is because a smaller network does not imply the degree of meshing to be different. The end-to-end label will be shorter in smaller networks because the number of hops is smaller (for a 16 nodes network: 6 hops * 3 bits) 18 bits while in the 28 nodes network (8 hops * 3 bits) 24 bits.

Label stacking

A common way of reducing the number of labels in the network is label stacking. Based on the knowledge that the itinerary of LSPs can partially overlap, it is possible to merge these LSPs into one with one label, stacked in front of the individual LSP label (that is hidden when the LSP is aggregated into a bigger one).

It seems that using label stacking in areas of the network with lots of transit traffic could bring a label length reduction on the local label to be investigated but not on the overall label-length. We compared the basic European Network with a network in which we have replaced the original links to the most heavily dimensioned node (in this case Berlin) with a virtual full mesh between its neighbours (see Fig. 18). To reduce the dimensions in the node Berlin, we will aggregate the original LSPs passing the node Berlin in LSPs going directly from one neighbour to another. What happens is that the original tributary LSPs get a second label (the stacked label) that allocates them to a certain aggregated LSP.

Only when the packet enters the cluster of nodes mentioned before it gets this second stacked-label for routing, implying the LSPs are aggregated. The original tributary label is then hidden but not removed so it can retake its routing task as soon as the packet leaves the clustered nodes. The stacked label can be much

Fig. 16 Number of correlators. Values represent the comparison in the requirements of the biggest nodes in the network

Fig. 17 Bit comparison on two networks with different number of nodes. Values represent the comparison in the requirements of the biggest nodes in the network

Fig. 18 Replacing Berlin and its neighbours by a virtual full mesh

Fig. 19 Number of bits for labels (in the node Berlin) in the network without and with label stacking and the number of correlators in the node Berlin (before and after label stacking)

shorter. Berlin has six ports (five to its neighbours and an add/drop port) so this second label only needs three bits (if we take the number of ports as a measure to define the number of bits in the stacked label). This is the label that has to be distinguished in Berlin to decide to which port the incoming packet to swap. This implies there are only six different correlators needed to implement in each of the AOLS-blocks of the node Berlin. On top of

that, we were able to reduce the maximum number of bits in the original label (that is used in the other part of the network), so the dimensions of the other nodes will also be reduced. This can be seen in the left graph of Fig. 19 where the number of bits in the label in the Basic network (no label stacking) are compared to the number of bits in the labels in the network with label stacking. The full Mesh over Berlin label is divided into

two parts. The upper part is the stacked label of three bits. The lower part is the tributary label used in the other part of the network. It is clear that Label Stacking thus causes the overall label-length to be longer (see Fig. 19) but it makes very heavily dimensioned nodes scalable. The latter can be seen on the right graph of Fig. 19, where the number of correlators in the node Berlin (before and after label stacking) is depicted. We see the biggest benefit when neither the port, nor the wavelength is used as implicit routing information. On the other hand, we could foresee design changes in the AOLS-blocks installed in the neighbour nodes of Berlin. They should be able to stack/pop the stacked label for the LSPs going to/coming from Berlin. Note that it seems hardly possible to combine label stacking with the label stripping approach. This is a topic that will be addressed for further study.

Conclusions

In this paper, we introduced a new label switching strategy. Label stripping seems to be a promising switching approach when it comes to reducing the number of labels, the label length and the resource requirements of the individual nodes in an optical network. Besides the comparison of label stripping and the current approach of label swapping on the before mentioned points we also carried out a study to map the influence of the network topology, number of nodes and label stacking on the label length and resources needed.

We made a distinction between the label length of the local label and the end-to-end label. From a node point of view, the local label length will define its dimensions. For that purpose, the best would be to have a local label length as short as possible. The latter reason is why label stripping is the most promising approach in obtaining scalable AOLS-blocks. The drawback of this approach is that the end-to-end label length is several times the local label length, and the overhead introduced by this label stripping approach is of more importance than in the label swapping.

By changing the networks degree in meshing, we can make a slight difference in the label length (both end-to-end and local label). By use of label stacking the local label length improves, although the end-to-end label is longer because it is the concatenation of the stacked label and the original label.

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