

Performance Evaluation of Overspill Routing in Optical Networks

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Abstract— We present a detailed performance evaluation of a hybrid optical switching architecture called **Overspill Routing in Optical Networks (ORION)**. The ORION architecture combines wavelength and (electronic) packet switching, so as to obtain the advantages of both switching paradigms. We have developed an extensive network simulator where the basic features of the ORION architecture were modeled, including suitable load-varying sources and edge/core node architectures. Various aspects of the ORION architecture were studied including the routing policies used (i.e. *once ORION always ORION* and *lightpath re-entry*) and the various options available for the buffer architecture. The complete network study shows that ORION can absorb temporary traffic overloads, as intended, provided sufficient buffering is present.

I. INTRODUCTION

The advent of WDM technology has resulted in transmission capacities that have increased manifold in recent years. Switching capacities and (line) speeds have, however, trouble keeping pace, resulting in networks in which fiber bandwidth is not efficiently exploited. It is the router/switch throughput that really transforms the raw bit rates into effective bandwidth, and current switching technologies are typically capable of handling line rates of up to 40 Gb/s. Various technologies such as optical packet switching (OPS) and optical burst switching (OBS) have been proposed to overcome this (electronic) switching bottleneck. Although very promising, most of them suffer from the absence of a reliable optical memory, equivalent to the electronic RAM, making these technologies not, or only partially, commercially deployable.

Another route is hybrid solutions, which try to combine the merits of wavelength switching with those of optical packet switching. Various schemes have been proposed so far for a hybrid optical switching system including the *polarization based* concept [1], the *light-trail* [2] and the *lightbus* concept [3]. Another significant new hybrid approach is called **Overspill Routing In Optical Networks (ORION)** [4]-[6].

In this paper, we present the first detailed network wide

performance evaluation of the ORION switching architecture on the NSFnet topology, and evaluate two routing policies, called *once ORION always ORION* and *lightpath re-entry*.

To this end, we have developed a discrete-event simulation using the ns-2 platform, where we modeled suitable edge- and core-router architectures, as well as load varying sources to simulate temporal, traffic overloading scenarios. Our results show that when sufficient buffering is available, ORION can indeed absorb temporary traffic overloads.

The rest of the paper is organized as follows. Section II presents the ORION switching paradigm as well as the two considered routing policies. Section III discusses the simulator architecture, while Section IV presents performance evaluation results.

II. OVERSPILL ROUTING IN OPTICAL NETWORKS

A. ORION architecture

ORION is based on a reconfigurable wavelength switched network, which can react to long term traffic pattern changes of hours, or even days, by reconfiguring the wavelength paths. Additionally, ORION allows full sharing of all wavelengths on a link, obtaining significant statistical multiplexing gains.

In order to cope with short term temporal traffic imbalances, ORION enables selective and transparent insertion/removal of data on the wavelength paths that cross ORION-enabled nodes. This ability results in a network that operates preferably like a wavelength switched network, but if necessary (when congestion arises) as a packet switched network. The basic idea is to forward IP/MPLS packets in a wavelength switched network, but change the switching operation when the provided wavelength paths are temporarily overloaded. In that case the excess data are sent in *overspill* mode and thus operate the network in packet switching mode. By instantly switching between the two operating modes, the load in the IP/MPLS routers is low, since most traffic can be sent through a direct wavelength path, but still allow maximal resource sharing since all wavelengths are still accessible if needed.

Figure 1 illustrates how this principle works in practice. Suppose A – C on λ_1 is a direct wavelength path, as well as A – B and B – C on λ_0 . All paths have a capacity of 10 Gb/s. Under normal conditions all traffic from A destined to C will

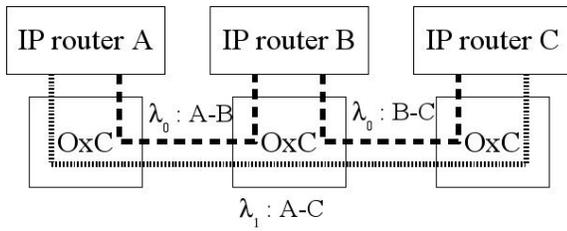


Figure 1: ORION switching paradigm: In the case that λ_0 wavelength channel of A-to-B connection overloads, packets from A to B are sent in “overspill” mode over λ_1 wavelength channel, although λ_1 is a direct wavelength path from A to C.

pass B transparently. Now assume A has temporally 12 Gb/s of traffic for B. In a usual wavelength switched network this would result in loss, as there is only 10 Gb/s available. In ORION, however, the remaining 2 Gb/s can also be served by forwarding these data in overspill mode over wavelength λ_1 in possible idle periods (when there is unused capacity). Since overspill data are treated like a packet-switched network, they will reach the IP router of destination B and thus be extracted instead of bypassing it. In order to do so, a specific node architecture is required as described in [6]. In the context of this paper, the implementation feature that needs to be mentioned is the presence of a marker on each packet. This marker indicates overspill packets, and can be easily identified, set, and erased by all nodes in the ORION network.

B. ORION Routing Policies

Within the ORION architecture, several options are possible on the way overspill traffic is handled. These options, termed routing policies, dictate if, how, and when packets should leave overspill mode, and go back to the wavelength switched regime. The different policies in some cases lead to different requirements in the control architecture, as well as to different hardware requirements [5]. In this paper we evaluated two basic routing policies:

- **Once ORION always ORION:** In this routing policy a packet which has entered overspill mode remains there. Thus, hop-by-hop routing is performed at every node and the overspill packet is treated at every node by the electronic router. These packets are stored in overspill buffers and evidently, have to look for an idle period at every hop. Operationally, *once ORION always ORION* is the simplest routing policy, but increases the electronic processing of packets at each node and also increases the end-to-end packet delay.
- **Lightpath re-entry:** As an overspill packet progresses towards its end destination in the network, it can occur that it reaches an intermediate node that has a wavelength path ending to the same destination. In that case, under the lightpath re-entry policy, the node inserts the overspill packet into this wavelength path. The packet is not marked as overspill and is transported all-optically to its destination. The advantage is that subsequent nodes, no longer see the overspill packet, which increases the routing efficiency and minimizes the delay. On the other hand,

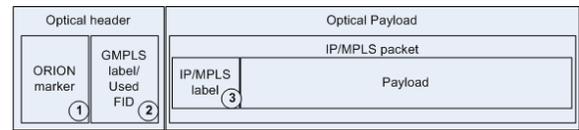


Figure 2: ORION packet form

lightpath re-entry is a more complex policy as it requires state information to be maintained and additional operations to be performed on overspill packets. For example, to facilitate matching between overspill packets and lightpath destinations, the edge/core routers have to employ Virtual Output Queues-VOQs (one queue per destination).

These two policies are not the only possible ones, but they have an advantage in that they can be implemented with a simple marker that indicates the overspill packets [7]. Other, more efficient policies are certainly possible, but they usually require additional functionalities at the nodes. A third policy, called *sub-lightpath* routing, which employs address matching on the overspill labels to allow the extraction of overspill packets before their end-destination, but beyond the next hop, is currently under investigation. This would enable the network to utilize all available wavelength paths at each node, not only those sharing the same destination.

In the next section, we provide an overview of the modules that were implemented in the simulator.

III. ORION NODE ARCHITECTURE AND CONTROL ACTIONS

A. Packet Format

Overspill packets were encoded using a custom packet format as shown in Figure 2. The overspill optical marker, field 1, specifies whether the packet is in overspill mode, while header field 2 (GMPLS label) defines the lightpath (LSP) that the packet is traveling in. In the actual case of an optically labeled switching network, the GMPLS and ORION optical labels are both encoded in the optical domain [7]. A node extracts and processes only the optical label, while payload remains in the optical form.

B. ORION Edge Router architecture and control action

Figure 3 shows the edge router (ER) architecture, implemented in the ORION simulator. The ER handles requests from flows and establishes lightpath connections. In the current implementation, RSVP-TE is used for setting up the lightpaths. ER maintains a table of the active LSPs and their associated network paths. Thus, it is aware of the links and intermediate nodes that are being used by each flow. Further, it incorporates a “void detection” module that “listens” to a fiber delay line (FDL) in order to detect idle periods in the LSPs. This FDL should be at least the maximum packet size.

The data of each flow is forwarded to a separate Random Early Detection (RED) queue ([8]) that is connected to the optical edge router. The RED queue detects incipient congestion by computing the estimated queue size \bar{q} ; if

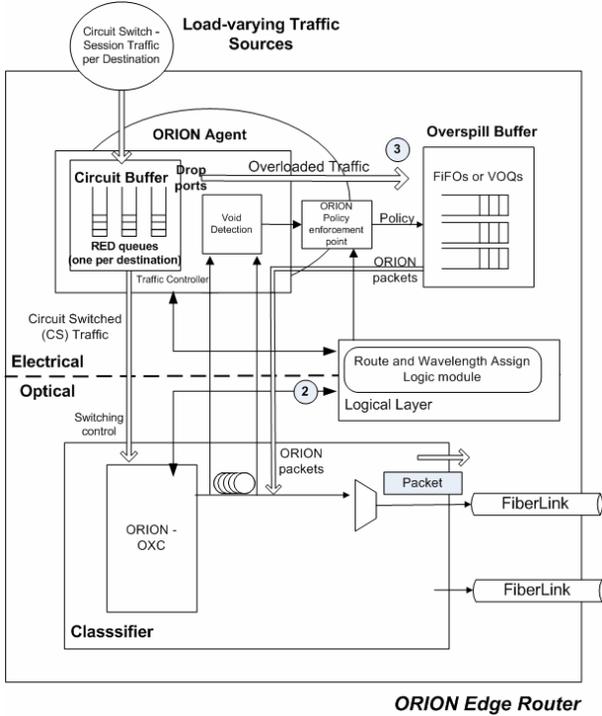


Figure 3: Edge router architecture. The numbers refer to the ORION packet fields that are being processed.

\bar{q} exceeds a predefined threshold (q_{min}) it drops incoming packets with probability P_a . The average queue size is calculated for each packet arrival by: $\bar{q} = (1 - w_q) \cdot \bar{q} + w_q \cdot q$, where q is the current queue size and w_q is a weighting factor. Assuming $P_b = p_{max} \cdot \frac{\bar{q} - q_{min}}{q_{max} - q_{min}}$, where p_{max} is the maximum dropping probability, P_a is given by:

$$P_a = \begin{cases} \frac{P_b}{1 - C \cdot P_b} & \text{if } q_{min} \leq \bar{q} \leq q_{max} \\ 1 & \text{if } \bar{q} > q_{max} \end{cases},$$

where C is the number of arrivals since the last drop. In our case, the drop ports of all the RED queues of the ER are connected with the overspill mechanism, which collects the *salvaged* packets and stores them in a dedicated “overspill buffer”. The implementation of this buffer depends on the routing policy enforced. For *once ORION always ORION* routing, the FIFO property per outgoing link is maintained, while for *lightpath re-entry* the buffer is implemented as a separate FIFO per destination (VOQ).

In general both the lightpath and overspill mode of operation can have a buffer. This leads to the following possible combinations:

- **No Buffering (NB):** When a packet of a connection finds its lightpath occupied, it is immediately put in overspill mode provided that ORION is enabled. In the case of *No-Buffering*, there is no overspill buffer and thus the overspill packet has only one immediate attempt to find an idle wavelength. If this is unsuccessful, or ORION is disabled, the packet is dropped.

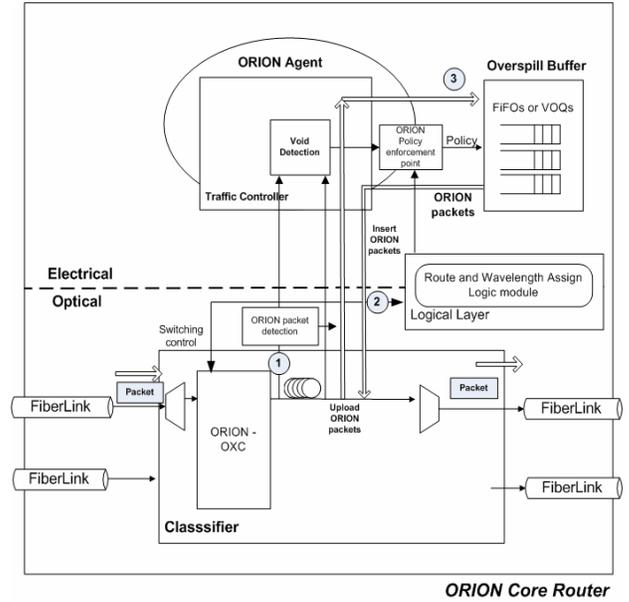


Figure 4: Core router architecture. The numbers refer to the ORION packet fields that are being processed.

- **Circuit buffering (CB):** Each lightpath has an associated RED queue for its packets storage. When a packet of a connection is dropped from the RED queue (and ORION is enabled) it tries to go immediately into overspill mode. If this is not feasible, or ORION is not supported, the packet is discarded.
- **Overspill Buffering (OB):** The dual of the previous regime: a packet immediately tries to enter its lightpath. If unsuccessful, the packet becomes overspill and is stored in a buffer, while the node starts looking into the passing through LSPs, to find an idle gap to insert it. As described earlier, when the *once ORION always ORION* policy is used, *OB* is implemented as a single FIFO per outgoing link, while *lightpath re-entry* uses VOQs. If the *OB* buffers overflow the oldest packet is discarded.
- **Circuit Buffering and Overspill Buffering (CBOB):** This is the combination of *CB* and *OB*, where RED queues are used for LSP data and FIFO or VOQ queues (depending on the policy) are used for overspill packets.

Note that, in the edge router, and in the case of *lightpath re-entry* policy, overspill packets are looking for possible idle periods in their own, original LSPs. However, in the intermediate core routers, overspill packets can be loaded on any LSP passing through the node and heading for the same destination.

After this general overview, we provide a short description of the specific modules present in the edge router architecture. The design is based on work presented in [9].

Route and Wavelength Assign logic module: This module calculates the routing paths using the Dijkstra shortest path algorithm and is responsible for establishing the lightpaths. It also maintains a table with the network virtual topology.

Traffic Controller module: This module handles wavelength switched data. It communicates with the *Route and Wavelength Assign logic* module to set up a new LSP and then forwards wavelength switched traffic. When a time-gap in an

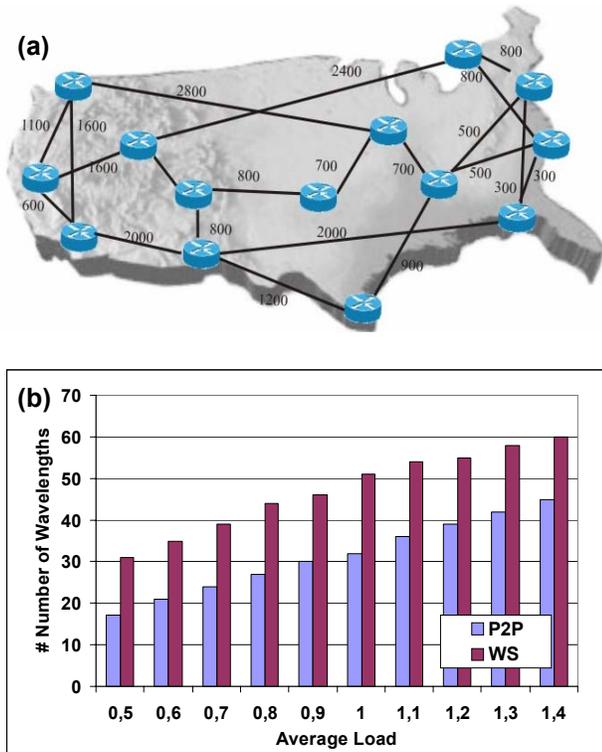


Figure 5: (a) 14-node NSFnet backbone network topology (the shown distances are in km) and (b) number of wavelengths per average load needed to support the communication of all source-destination pairs with shortest path routing in the case of wavelength switching (WS) and point-to-point packet switching (P2P), for 0.01 loss ratio.

LSP is detected, an overspill packet from the appropriate overspill queue is inserted in that specific LSP.

Classifier module: The classifier module is responsible for receiving and forwarding packets depending on their header information. In the ORION network simulator, the Classifier accesses the packet header fields 1 and 2 (see Figure 2) and performs the appropriate forwarding/routing actions.

C. ORION Core Router architecture and control actions

The operation of the Core Router (CR) is similar to that of ER but it additionally involves the detection and extraction of overspill packets from the LSPs. Figure 4 shows the architecture of the core router module implemented in the simulator. For the execution of the routing/forwarding ORION policy, the core node maintains a table with the active LSPs and their associated paths, similar to that maintained at the ER. If the core router identifies an overspill packet, the node extracts it from the passing through LSP and stores it into the corresponding FIFO or VOQ. Control actions are identical to those of the ER, except for the handling of locally incoming traffic. Thus, all possible buffering architectures of NB and OB are supported.

IV. NETWORK LEVEL PERFORMANCE EVALUATION

The evaluation of the ORION architecture was performed assuming the NSFnet backbone network topology, shown in Figure 5(a). All links were assumed to be bidirectional, with a 1 Gbps capacity per wavelength, to reduce simulation times.

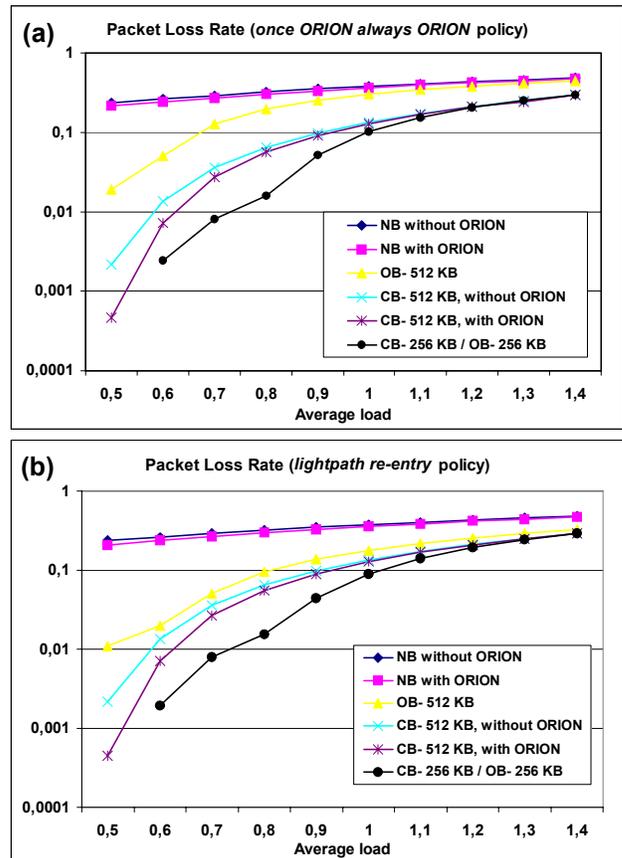


Figure 6: a) Packet loss rate for hop-by-hop routing policy and the supported buffering schemes versus average source load. b) Same set of results in the case of lightpath re-entry policy.

With these assumptions we have measured the number of wavelengths needed to support all traffic with a 1% packet loss ratio, in the case of a pure wavelength switching (WS) network as well as in the case of a point-to-point packet switching (P2P) network. Figure 5(b) shows the corresponding results. The minimum number of wavelengths needed to support all source-destination pairs with an individual lighpath can be calculated to be 31. This number of wavelengths was used in the simulation experiments in order to show the degree to which overspill mechanism can absorb temporal traffic imbalances.

We modeled communication between each source-destination pair as a single separate traffic source. Each source generates packets according to a Poisson process with packet sizes drawn from a typical Internet mix packet size distribution (40, 520, 1500 Bytes of 50%, 37.5% and 12.5% occurrence respectively). The load of a traffic source, was defined as the ratio of ON-to-OFF periods, that can exceed 1.0 to simulate path overloading. Every source selects its load randomly – according to a uniform distribution with a given average value λ and a standard variation equal to 0.5. This randomly chosen load was maintained throughout a simulation cycle.

In the simulations carried out, a separate RED queue was maintained for each source-destination pair and its total size per edge router is depicted as “CB” buffer size. The chosen RED queue parameters are: $w_q=0.001$, $q_{min}=0.7$ RED_size, $q_{max}=$ RED_size and $p_{max}=0.2$. In the experiments, opto-

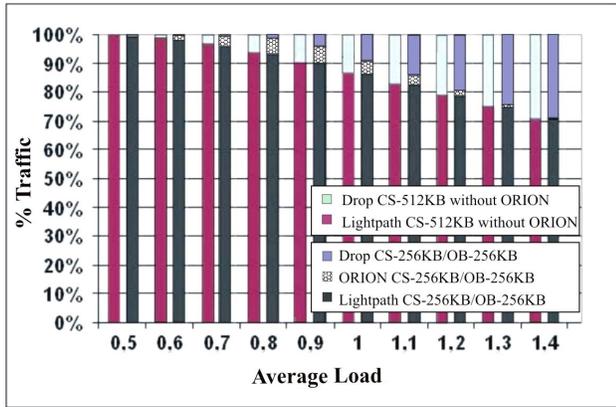


Figure 7: Traffic statistics for re-entry policy. (a) $CS = 512$ KB without ORION and (b) $CS = 256$ KB, $OB = 256$ KB.

electronic conversion time was set to 0.01 msec, while the fiber delay length for gap detection inside the nodes ([6]) was set equal to 0.04 msec, resulting in an average propagation delay through the network of 13.1 msec.

The key performance metrics measured include packet loss for the various buffering schemes, overspill throughput, and average end-to-end delay. All these were measured versus the given average source load for both ORION routing policies.

Figure 6(a) and (b) show the packet loss ratio of the *once ORION always ORION* and the *lightpath re-entry* policies for the various buffering schemes. The number besides the acronym of each buffering scheme shows the employed buffer size in Kbytes. As expected, all cases of *NB* (with or without ORION support) exhibit the highest loss ratio since in that case packets are dropped immediately after a temporary overload of the wavelength switched paths. The loss ratio of all cases without ORION (*NB without ORION* and *CB-512KB without ORION*) do not depend on the chosen policy (actually there are no overspill packets) and thus are identical in both Figures 6(a) and (b).

With only *Overspill Buffering (OB-512KB)*, the *lightpath re-entry* policy outperforms *once ORION always ORION*. In this buffering scheme, a large part of incoming traffic (20%-40%) tries to switch to overspill mode. Since the buffers of any intermediate node can be (or close to) be congested, *once ORION always ORION* policy exhibits a higher loss ratio. On the other hand, packets that re-enter a lightpath are treated more favorably in the sense that they are transparently forwarded to their end destination and thus avoid possible congested, intermediate nodes.

Regarding the two cases of *CB-512KB with ORION* and *CB-256KB/OB-256KB*, both policies exhibit similar performance characteristics, since in these cases the overspill traffic is only a small percentage of the total traffic.

With respect to performance of the individual buffering schemes, *CB-256KB/OB-256KB (CBOB buffering)*, significantly outperforms the others. The comparison of this combined scheme with the *CB-512KB without ORION* reveals the positive effect of overspill routing. It is evident from Figure 6, that using the same 512KB buffer, but dividing it into two equal parts for *Circuit Buffering (CB)* and *Overspill*

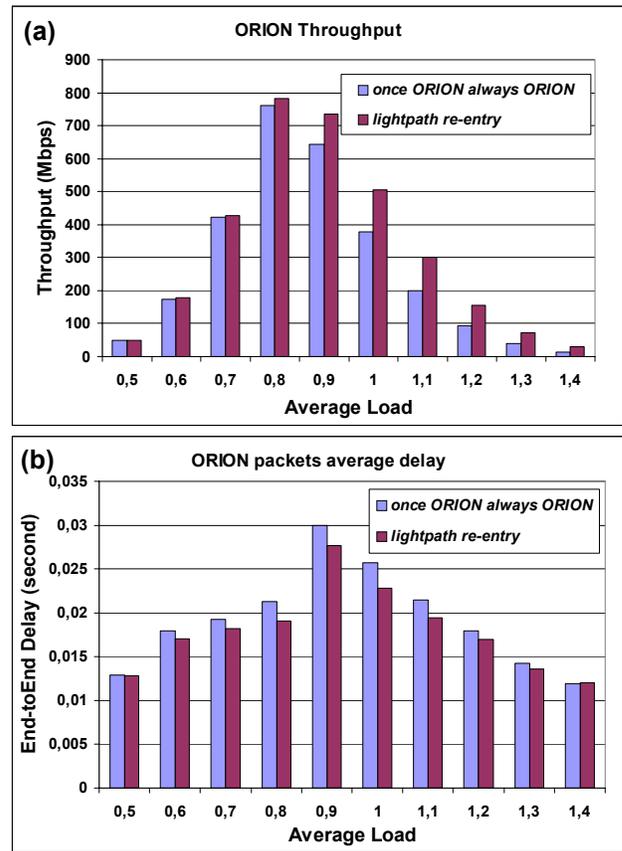


Figure 8: (a) Throughput of ORION traffic and (b) average end-to-end delay, versus average load for the two policies.

Buffering (OB), results in a reduction of the loss ratio.

Figure 7 shows the corresponding traffic statistics for the *lightpath re-entry* policy, for the cases of *CB-512KB without ORION* (left columns) and *CB-256KB/OB-256KB* (right columns) schemes. In particular Figure 7 illustrates the percentage of packets dropped or transported in overspill mode. It can be seen that overspill mechanism is more effective for loads between 0.8 and 1.0. This was expected, since above a certain load, all LSPs become saturated, void filling cannot be performed and thus the beneficial effect of overspill routing eventually disappears.

To further compare the two ORION routing policies, we have measured the throughput and average packet delay obtained for the best performing *CB-256KB/OB-256KB* scheme. Figures 8 (a) and (b) show the corresponding results. It can be seen that for source loads higher than 0.8, the *lightpath re-entry* policy outperforms *once ORION always ORION* in both throughput and delay, since a fraction of overspill traffic reaches its destination immediately and fewer packets are uploaded at intermediate nodes. This packet insertion/extraction process increases the dropping probability and further increases the end to end delay as well. Figure 9 shows the number of overspill packets that are extracted at intermediate nodes per second for both policies. This is the additional traffic seen by the electronic part of the core routers due to the overspill mechanism. The difference in the extracted packets between the two policies reveals the actual number of

overspill traffic that was “re-entered” in the lightpaths.

Note that for low average loads, packets that try to go into overspill mode is only a small fraction of the total traffic, explaining the low throughput and delay levels. As load increases, throughput increases as well reaching its maximum value for workloads close to 0.8 - 0.9. Above this, throughput steadily decreases for both policies, since network saturates and thus there is no bandwidth to be reused. With respect to end-to-end delay (see Figure 8 (b)), it can be noted that the maximum value corresponds to the same workload range (0.8 - 0.9). Above this range, overspill packets start getting dropped, and thus gradually are given limited chances to switch to overspill mode, independently of the policy enforced. Overspill packets that follow paths with a small number of hops have higher probability to reach their destination, and thus delay decreases for load higher than 0.9, while one should expect delay to continue to increase.

Finally, we have investigated the effect of the total buffer size (RED queues for *Circuit Buffering* and FIFO/VOQ queues for *Overspill Buffering*). Figure 10 shows the loss ratio of the *lightpath re-entry* policy. The improvement in the loss ratio differs for the various supported buffering schemes, and higher gains are observed for the combined *CBOB* scheme. An important note here is that the performance differences between the buffering schemes remain, regardless of the size of the buffer. To this end, even though the necessary buffer size depends on the network load, it is clear that both types of buffering are necessary for an efficient performance of ORION.

V. CONCLUSIONS

In this paper, we have presented a detailed performance evaluation of the ORION hybrid switching architecture using a network simulator platform developed for this purpose. We have evaluated two routing policies available within ORION, and looked at various buffering schemes. According to our results the *lightpath re-entry* policy, combined with the *Circuit Buffering Overspill Buffering (CBOB)* scheme is superior to all other combinations in terms of loss ratio, throughput and packet delay. The simulation results revealed that the overspill mechanism is capable of absorbing temporary network imbalances, as long as the entire network is not overwhelmed with traffic. Future work includes the study of the *concentrator*, an O/E interface that limits the number of overspill packets that can be simultaneously uploaded in a node [6].

VI. ACKNOWLEDGMENTS

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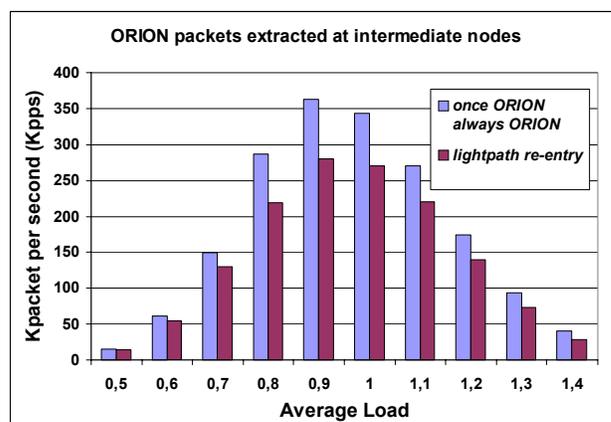


Figure 9: Number of packets uploaded at intermediate nodes.

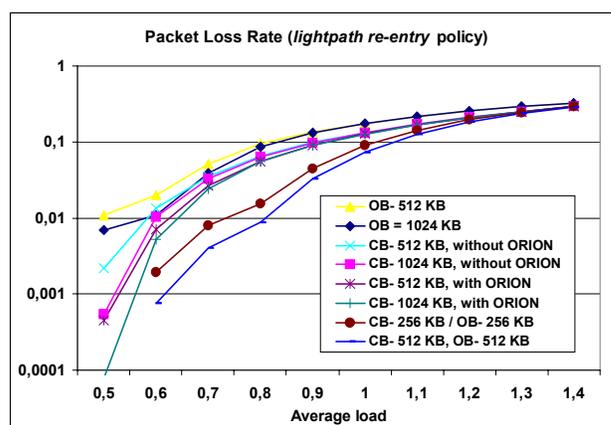


Figure 10: Packet loss rate for lightpath re-entry policy for various buffering schemes with 512KB and 1024KB buffers.

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