Novel contention resolution technique for QoS support in connection-oriented optical packet switching

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***Abstract*— This paper considers an optical packet-switched node with limited buffer capabilities and subject to asynchronous, variable-length packets and connection-oriented operation. In such a scenario, we address the problem of providing QoS. While existing solutions focus on applying some form of resources reservation on top of the contention resolution algorithm, here we propose a novel method: given a set of K categories of service to be provided in the network, K different contention resolution algorithms are implemented to cope with the requirements of such service categories. In this paper, we define three different OPS service categories based on three different contention resolution algorithms, we design an ad-hoc pool of fiber delay lines for such a scheme, and evaluate its performance by simulation. The obtained results indicate the merits of our method which opens up future interesting developments for a whole network scenario studies.**

I. INTRODUCTION

In recent years, packet switching approaches are gaining credibility as potential solutions for next generation Internet [1]. Instead of over-provisioning of circuits, the packet techniques directly in the transport network will bring more statistical sharing of the physical resources to reduce the connection costs. In case switching is performed all-optically and data remains in the optical domain during the entire source-destination path, the concept is referred to as optical packet switching (OPS) [2]. This is a long-term optical networking solution offering the finest and the most flexible access to the optical bandwidth.

Since OPS is based on statistical multiplexing, packet contentions may arise at the nodes. Therefore, a contention resolution policy must be applied to reduce the packets losses and make the statistical multiplexing more efficient. Contention resolution techniques typical exploit space domain, by means of deflection routing, frequency domain, by means of wavelength multiplexing, and time domain, by means of optical queuing. The lack of optical RAMs imposes the use of a pool of fiber delay lines (FDLs) which are bulky and not scalable and offer limited buffering capabilities (few tens of delays at maximum [1]).

Recent works (for instance [3] [4]) suggest that the integration of a connection-oriented path management protocol on top of the contention resolution algorithm can both improve the network performance and reduce the control complexity. In this context, protocols such as MPLS can be effectively extended to the OPS environment to provide a distributed management scheme able to setup and maintain Optical Virtual Connections (OVCs).

In this paper we focus on this scenario and in particular we deal with the QoS provisioning problem. Existing works have largely focused on the following method: 1) design a contention resolution algorithm which minimizes the Packet Loss Rate (PLR) under single class scenario, thus 2) apply a QoS mechanism to differentiate the PLR among two or more classes. Given that we are dealing with a connection-oriented model, here we suggest a novel method based on the well known ATM scheme which consists of defining different service categories, each one based on a different contention resolution algorithm specifically designed to cope with the requirements of that category. With this technique, besides the PLR, also the preservation of the correct packet sequence and the computational complexity can be considered as important metrics for the QoS provisioning problem.

The remaining of the paper is organized as follows. Section II introduces the reference scenario describing the details of the connection-oriented OPS network model. In Section III we present the simulation environment in order to explain the different switch parameters and performance measures of interests. Section IV describes and evaluates the novel method based on defining service categories and different contention resolution algorithms. Section V concludes the paper.

II. NETWORK REFERENCE MODEL

The connection-oriented OPS network comprises several nodes connected in a mesh topology. Based on destination address and QoS requirements, packets coming from client networks are classified at the edge nodes into a finite number of subsets such as the *Forwarding Equivalent Classes* (FECs) concept defined in MPLS environment. Each FEC is identified by an additional *label* added to the packets. Edge nodes setup and maintain unidirectional OVCs throughout the network. Packets belonging to the same FEC are identical from a forwarding point of view and are transferred from source to destination along the OVC which corresponds to their label. On each core node, a simple label matching operation is performed on a pre-computed OVC forwarding table, thus simplifying and speeding up the forwarding function.

We assume that each node (either edge or core) is an optical packet switch with full connectivity and wavelength conversion. It is capable of switching asynchronous, variable-length packets [6] allowing a better interworking with heterogeneous client traffic [7]. The switch acts as an output queuing switch using a feed-forward configuration [8] with the optical buffer made by B FDLs. Since the optical technology is still in its infancy, some devices for this architecture are today not available. Nonetheless it is reasonable to foresee that they will be fully developed when OPS (which is a long-term solution) is in place.

The nodes have an electronic Switch Control Logic (SCL) which takes all the decisions regarding the configuration of the hardware to realize the proper switching actions. On one hand it is in charge of setting the forwarding table when a new OVC is established. This problem is not addressed here and we assume that at the OVC setup a routing protocol assigns the output port while the GRP procedure proposed in [5] selects the output wavelength. On the other hand it runs a contention resolution algorithm when a new packet belonging to given OVC arrives to the switch. In this case, the label is extracted and the functions performed by the SCL are:

1) Lookup the forwarding table to determine the output port n^{out} (which determines the network path) and the output wavelength λ^{out};
2) If λ^{out} is busy:
    a) find the set of wavelengths $\Lambda \in n^{out}$ not busy;
    b) if $\Lambda = \emptyset$, then the packet is lost
    c) if $\Lambda \neq \emptyset$, select a new wavelength $\lambda^{out}_{new} \in \Lambda$;
3) Determine the delay D_j and select the FDL j;
4) Transmit the packet to FDL j with wavelength λ.

The selection of the wavelength in step 2.c is the key point of the contention resolution algorithm and can be implemented by following different policies:

- **Static**. The OVC is assigned to a wavelength at OVC setup and this assignment is kept constant all over the OVC life. Therefore packets belonging to the same OVC are always switched to the same wavelength and the contentions can be only solved in time;
- **Dynamic**. The OVC is assigned to a wavelength at OVC setup but it can be changed during OVC life. When heavy congestion arises on the assigned wavelength (i.e., when the time domain cannot solve a contention), the OVC is temporary switch to another wavelength. When congestion disappears, the OVC is switched back to the original wavelength.

These policies have different features. As we stated in the introduction, we are interested in three parameters: PLR, the complexity and the preservation of the correct packet sequence. The complexity of the algorithm must be carefully regulated because may lead to overloading problem on the SCL. On the other hand, the out-of-order delivery of the packets is a serious problem because causes both expensive reordering operations and the use of very large electrical memories at the edges of the optical network. Since the OPS node uses very short optical buffers and the propagation delay cannot be reduced, rebuilding the original information is the main contribution of the packet delay and, as demonstrated in [9], causes throughput degradations at the application level.

Analyzing these aspects with the different policies we can observe that the static wavelength selection requires minimum control complexity since processing is performed only at OVC setup. At the same time, it preserves the correct order of packets belonging to the same OVC since new arrivals cannot overtake older packets. However it does not optimize the resources obtaining high PLR figures. On the other hand, when a dynamic algorithm is executed, the OVC is switched to an alternative wavelength that is not (or is less) congested and new incoming packets on that OVC will experience in general less queuing time than older packets and will very likely overtake them along the network path. At the same time, the amount of execution of the algorithm affects the processing load on the SCL ranging from no efforts if static approach is used to fairly demanding efforts if a new wavelength search is executed per each incoming packet (e.g., [7] [10]).

According to these observations, we develop our QoS technique in Sec. IV.

III. SIMULATION ENVIRONMENT

In this section we present the simulation environment adopted to evaluate the performance of the solutions described in the following sections. It consists of an event-driven program which simulates the behavior of a single optical packet switch. We do not deal with implementation issues but with performance analysis, hence we consider that a non-blocking OPS switch architecture with full wavelength conversion capabilities is available. The parameters of which are:

- N, the number of input and output fibers;
- W, the number of wavelengths per fiber;
- C, the transmission birate;
- $\mathbf{Q}_B$, the set of possible delays of B FDLs; if the delays are consecutive, the buffer is said *degenerate*, otherwise, it is *non-degenerate* [8];
- D, the delay granularity of the FDLs;
- L, the average number of LSPs per input wavelength.
- ρ, the offered load which is the same for any input and output wavelength (i.e., uniform distribution).

The distribution of the LSPs follows an exponential model: both the interarrival time and connection duration are exponential distributed. The mean value of the interarrival times, connection duration, and required bandwidth are selected accordingly to generate the required offered load ρ.

The interarrival time of the packets is exponential distributed with a mean that depends on the LSP bandwidth. The packets have an exponential distributed size with average and minimum lengths of 500 and 40 bytes respectively. The number of simulated packets is chosen big enough to reach steady-state results.

We define the following measures to evaluate the performance of the switch:

- *Average Packet Loss Rate* (PLR). It is the usual performance measure for packet switches and also indicates the capability of an algorithm to reduce the congestion situation.
- *Out-of-Sequence packets* (OS). This measure indicates the percentage of out-of-sequence packets belonging to the same LSP. The higher the percentage, the higher the amount of packets to be reordered at the destination.
- *Forwarding Opacity* (FO). It is measured as the percentage of packets that are forwarded searching a new wavelength over the total number of simulated packets. The resulting value estimates the overload on the switch control function. The higher the percentage, the higher the overload.

In the following performance evaluation sections, we will show only the most significant measures and results according to the purposes of the study.

IV. QoS PROVISIONING

A. Problem description and related work

The technology limitation of the optical queuing motivates significant research efforts in recent years dealing with the design of simple contention resolution policies able to provide QoS differentiation. The impossibility of pre-emptying packets already buffered makes unfeasible the implementation of conventional fair queuing scheduling commonly used in electrical switches. At the same time, QoS schemes must be kept very simple to be effective in OPS where each node must be able to schedule tens of Tbit/s.

The mechanisms proposed in literature use some form of resource reservation (either a buffer threshold [11] or wavelength threshold [12]), offset time [13] or hybrid electrical/optical buffers [14]. The first method presents not good enough results (for instance in [11] the PLR for low priority class is 10^{-2} with a load of 0.8). To achieve acceptable levels of PLR, the scheduling requires very high computational complexity or very large optical memories. The second one shows good results when applied to optical burst switching [15] where bursts comprise several packets. Nonetheless, it seems not effective in OPS where the overhead of the control packets introduces considerable bandwidth wastage. Finally, the third one is unviable since electronic devices cannot keep up with the speed of optical links and the O/E bottleneck is maintained.

In this paper, we propose a novel strategy able to improve the switch performance and provide the required QoS. The strategy is based on the fact that, in a QoS environment, it is not practical to provide the best handling to a traffic category that does not really require it. Therefore, if a set of K categories of service is available in the network, we suggest to implement a set of K different handlings (i.e., algorithms) in the switches. When a packet belonging to an LSP with category i arrives to a switch, the SCL will execute the corresponding algorithm i to forward the packet. We refer to this technique as *Service Category-to-Algorithm Wavelength Selection* (SCAWS).

B. Scenario

For this study, we consider a system with the following three categories of service:

- **Best Effort** (BE) with no requirements;
- **Loss Sensitive** (LS) for multimedia broadcasting applications which requires bounded losses;
- **Real Time** (RT) for interactive applications which requires strict performance (very low PLR and very short delay).

We hence design three algorithms to be implemented in the SCL. The algorithms are the following:

- **Two-State Wavelength Selection** (TSWS) to be applied to LSP transporting BE packets;
- **Losses Bounding Wavelength Selection** (LBWS) to be applied to LSP transporting LS packets;
- **Sequence Keeping Wavelength Selection** (SKWS) to be applied to LSP transporting RT packets.

The aim of the TSWS algorithm is to reduce the control overload (low FO) while maintains an acceptable level of the PLR. This algorithm tries to improve the performance of the static approach assigning two wavelengths to the LSP during the setup procedure (i.e., the GRP algorithm [5] is executed twice). This assignment is kept constant all over the LSP life and single packets are always forwarded to the less congested wavelengths. This means that the wavelength searching step of the contention resolution algorithm is never needed (FO is always 0%).

The aim of the LBWS algorithm is to achieve a bounded PLR. Each LSP is assigned to a wavelength at setup using the GRP algorithm. This assignment may change if the LSP experiences a PLR above of a predetermined value R (*required PLR*). For this scope, a window T is defined. Every T the algorithm computes the PLR of each LSP. These PLRs are then ordered in descending way; starting from the higher value, the algorithm compares the PLRs with R, if it is higher, a new GRP algorithm is executed to reassign the LSP to another wavelength. Clearly, the value of T affects the switch performance: too high values may not guarantee the required PLR; in contract, too low values can increase the control overload with an extreme situation of executing a new GRP algorithm per each incoming packet. It is important to notice that the value of R can be different from one LSP to another since their requirements can be distinct. For sake of simplicity we assign the same value to all LSPs.

The SKWS algorithm has been original proposed in [4]. Its aim is to achieve excellent level of PLR maximizing the resource utilization and throughput. At the same time, SKWS needs to control the delay preserving the correct packet sequence belonging to the same LSP. For the purpose of this work, given a stream of ordered packets at the switch input, we define the packet i to be out-of-order when the first bit of packet i leaves the switch before the last bit of packet $i-1$.

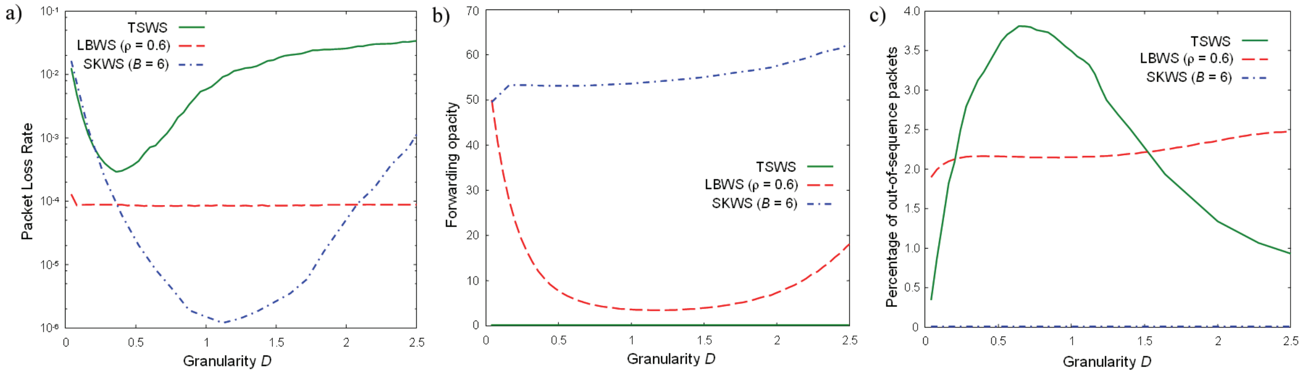

Fig. 1. a) Packet loss rate, b) Forwarding opacity, and c) Out-of-sequence packets as a function of D normalized to the average packet duration, comparing TSWS, LBWS and SKWS

Less restrictive cases are more difficult to control, especially when considering a cascade of switches. In fact, taking into account that, in general, the optical packets can aggregate more than one IP packet, the relative position of subsequent IP packets included in two subsequent optical packets cannot be controlled if overlapping is permitted. Therefore, a strict sequence keeping (i.e. avoiding packet overlapping) represents the unique procedure that assure the maintenance of sequence both at the optical packet level and at the IP packet level. Consequently in this work we have adopted this restrictive case.

To keep the correct packet order, the SCL stores the time-stamps t^{out} (one per each LSP) at which the last bit of the last packet is scheduled to leave the switch. This time is calculated as the sum of the packet arrival time, its duration and the delay assigned in the buffer. When a packet belonging to the LSP l arrives, the SCL recalls the time $t^{out}(l)$ and determine if the new packet needs additional delay to keep the order. Due to the discrete number of delays provided by the optical buffer, the additional delay is calculated as the integer multiple of D greater than $t^{out}(l)$.

In the next sections, the algorithms are evaluated separately in order to find their specific characteristics. Afterwards, we integrate them in the same switch and evaluate the SCAWS technique.

C. Evaluation under single-category of service

In the following figures, we consider a switch with $N = 4$, $W = 16$, $C = 10$ Gbps, and $L = 3$. The buffer configuration is a degenerate buffer $\mathbf{Q}_8$ (i.e., the length is $B = 8$) except for SKWS which uses a shorter buffer $\mathbf{Q}_6$. The offered load is $\rho = 0.8$, except for LBWS where it is $\rho = 0.6$ because it is not possible to bounding the PLR of high amount of traffic maintaining an acceptable control complexity. R is set to 10^{-4} and T to 20 D which are reasonable values offering a good trade-off between complexity and PLR.

Figure 1a) shows the PLR as a function of D normalized to the average packet duration, comparing the TSWS, LBWS and SKWS algorithms. In this figure we can see that SKWS achieves the better PLR of 10^{-6} with $D = 1.2$. Contrarily to the usual concave behavior shown by other algorithms, LBWS exhibits constant values less than 10^{-4} which is the value set as required. TSWS presents the worst PLR but it is important to remark that its aim is to have low control complexity.

Figure 1b) plots the FO measure comparing the TSWS, LBWS, and SKWS. It is clear that SKWS imposes the higher overload on the switch control; while LBWS shows low computational requirements reaching values close to 4%. The LBWS curve indicates that keeping bounded PLR require less computations for value of D ranging between $D = 1$ and $D = 1.4$, with a minimum in $D = 1.2$. Finally, TSWA does not need to reconfigure its LSP-to-wavelength assignment; therefore FO is always 0%.

Figure 1c) shows the percentage of out-of-sequence packets comparing the TSWS, LBWS, and SKWS algorithms. As expected, SKWS maintains the correct sequence delivering. LBWS presents values around $2 \div 2.5\%$ while TSWS exhibits a convex behavior with a maximum of 3.7% in $D = 0.7$.

D. Extension for multi-category of service

The results previously obtained assess the goodness of the proposed algorithms indicating that their aims have been fully accomplished: TSWS imposes low control overload and reaches acceptable PLR; LBWS requires low control overload and is able to guarantee a bounded PLR; finally, SKWS requires high control overload but achieves very good PLR maintaining the correct order of the packet sequence. The next step is hence the integration of these algorithms in the same SCL and the verification of the mutual impacts on the performance measures.

The integration is not trivial because the previous results also indicate that the algorithms achieve the better performance with different values of the fiber granularity D, the optimum D for LBWS and SKWS is 1.2 while it is 0.4 for TSWS (see Fig. 1).

However, we notice that the rate between these two optimum values ($D = 1.2$ and $D = 0.4$) is exactly 3. Extensive simulations (not presented here for lack of space) demonstrate that this peculiar factor of 3 is valid for whatever traffic matrix. Based on this factor, the integration of the different contention

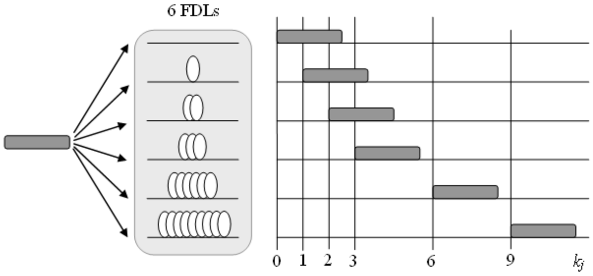

Fig. 2. Non-degenerate buffer configuration with 6 FDLs. BE packets can use delays $\{0, D, 2D, 3D\}$, while the RT and LS packets can use delays $\{0, 3D, 6D, 9D\}$

resolution algorithms can be done using the following buffer architecture. Firstly, we fix $D = 0.4$ and set up two degenerate buffers: $\mathbf{Q}'$ with $D_j = jD$ delays and length B' for the BE packets and $\mathbf{Q}''$ with $D_j = 3jD$ delays and length B'' for RT and LS packets. Then, these buffers are merged in a non-degenerate buffer $\mathbf{Q} = \mathbf{Q}' \cup \mathbf{Q}''$ in such a way that the delays that are common in $\mathbf{Q}'$ and $\mathbf{Q}''$ are available for any category. Figure 2 shows an example with $B' = B'' = 4$, and a resulting length $B = 6$ of buffer $\mathbf{Q}$.

E. Evaluation under multi-category of service

For the evaluation under multi-category, we set $N = 4$, $W = 16$, $C = 10$ Gbps, $\rho = 0.8$, $L = 3$, and, finally, the required PLR and measure window for LS packets to $R = 10^{-5}$ and $T = 20\ D$, respectively. Regarding the distribution of traffic, in Fig. 3, Table I and Fig. 4 we assume that 50% of the LSPs transport BE packets, 30% transport RT packets, and the rest LS packets. In Fig. 5 we analyze the PLR changing this distribution.

Fig. 3 plots the PLR for the entire system as a function of D normalized to the average packet duration. In the figure, we include secondary x-axis which indicates the granularity perceived by SKWS and LBWS algorithms (exactly 3 times D). As expected, any categories of service achieves the optimal PLR in correspondence of $D = 0.4$. Hence, we use this value to obtain the following results.

In Table I, we compare the SCAWS technique with the *Empty Queue Wavelength Selection* (EQWS) algorithm [3] - the best performed dynamic algorithm - and the *Minimum Gap* (MINGAP) algorithm [10] - the best performed connectionless algorithm. Both EQWS and MINGAP use the buffer threshold approach [11] to provide QoS (the values of D and of thresholds are those providing the lowest PLRs).

The results show that the SCAWS technique provides the lowest PLR for both LS and BE traffic. Moreover, as expected, the higher control complexity is required to forward the RT traffic (FO is 66.14%) while LS and BE impose low overload (5.93% and 0% respectively). In contrast, MINGAP imposes the same (very high) FO for any category, while EQWS requires higher FO for BE traffic which is an evident nonsense. At the same time, the packet sequence of RT traffic is preserved using the SCAWS technique, while it reaches 2% and 5% using EQWS and MINGAP, respectively. Previous studies [16] confirm that even a small percentage of out-of-sequence (like that caused by EQWS algorithm) may impact harmfully on the network performance. We must also consider that this percentage is counted at the output of a single switch; by assuming n switch in series along a path this percentage increases accordingly.

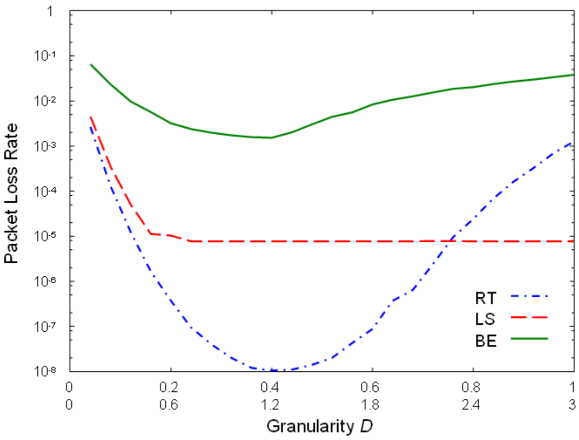

Fig. 3. Packet loss rate as a function of D normalized to the average packet duration.

Figure 4 plots the PLR as a function of the buffer depth B for any category. The results indicate that a significant improvement of the performance can be obtained with a small increase of the number of FDLs B of buffer $\mathbf{Q}$.

Finally, Fig. 5 shows the PLR changing the percentage of the relative load between the RT and BE traffic while maintaining fixed to 20% the relative load of LS traffic. This means that for instance, when the percentage of RT is 20%, the percentage of BE is 60%. We can see that the PLR of LS cannot be guaranteed if there is a high percentage of RT traffic (i.e., more than 60%). On the other side, if RT is not present, BE traffic is not able to fully exploit the switch capacity and the PLR remains relatively high. A way to improve the performance of the BE traffic when RT and LS present low loads is to apply the SKWS algorithm also to some BE LSPs. In this case, a smart policy should be developed in order to decide when, which, and how many BE LSPs can be forwarded according to the SKWS algorithm. This study is not developed here and is let for future investigations.

V. CONCLUSION

In this paper, we have considered an optical network integrating connection-oriented mechanisms and OPS technologies. In such a scenario, we have dealt with the packet contention problem under QoS requirements designing the novel SCAWS (Service Category-to-Algorithm Wavelength Selection) technique. In particular, we have defined a system with three different OPS service categories based on three different contention resolution algorithms. An ad-hoc buffer architecture has been designed to coordinate and optimize the behavior of the system. The obtained results highlight its

TABLE I

PLR, FO AND OS COMPARING SCAWS TECHNIQUE WITH EQWS AND MINGAP

	SCAWS			**EQWS**			**MINGAP**		
Category	**PLR**	**FO**	**OS**	**PLR**	**FO**	**OS**	**PLR**	**FO**	**OS**
RT	$1.08\ 10^{-8}$	66.14%	0%	$3.00\ 10^{-8}$	16.20%	2.02%	0	81.33%	5.39%
LS	$7.68\ 10^{-6}$	5.93%	1.76%	$2.75\ 10^{-4}$	30.82%	2.33%	$9.78\ 10^{-4}$	81.05%	5.03%
BE	$1.55\ 10^{-3}$	0%	3.29%	$5.24\ 10^{-2}$	52.51%	3.41%	$3.96\ 10^{-3}$	80.92%	4.62%

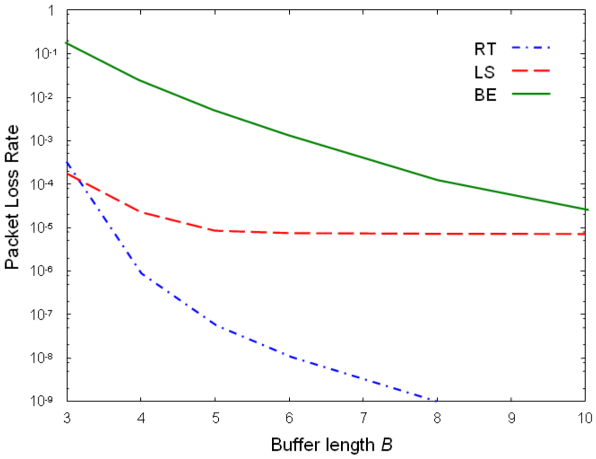

Fig. 4. Packet loss rate as function of the buffer length B.

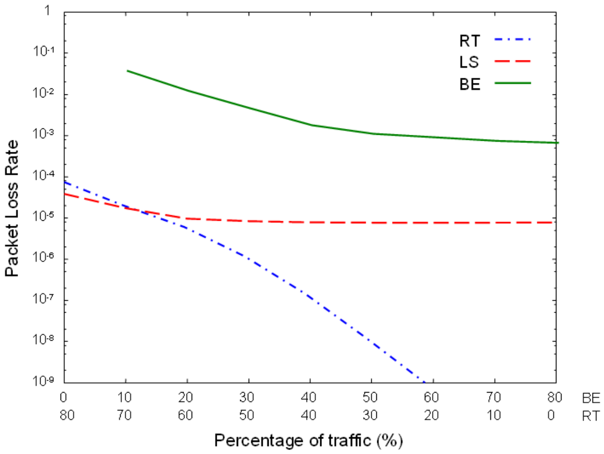

Fig. 5. Packet loss rate as function of traffic relative load percentage.

goodness compared to other approaches (i.e., the EQWS and MINGAP algorithms using buffer threshold technique).

Future works will deal with the integration of the quality differentiation method with the SCAWS technique in order to obtain a more flexible environment. At the same time, SCAWS opens up future interesting developments on the routing problem for a whole network scenario.

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