Protecting Real-Time Traffic Service in a 3-LIHON Hybrid Node

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Abstract— **Recently a new hybrid optical network, integrating circuit and packet transport services has been proposed. This network, called 3-Level Integrated Hybrid Optical Network (3-LIHON), provides different transport services for guaranteed, real-time, and best-effort traffic. This article proposes a protection mechanism for the real-time traffic in the 3-LIHON network. Indeed real-time traffic carries a small but important portion of the traffic, i.e. control traffic. The proposed scheme exploits the redundancy provided by 3-LIHON nodes, thus not requiring additional hardware, representing a cost-efficient solution. The availability achieved by this protection scheme is assessed by means of structural models, and a sensitivity analysis is performed. Simulation results measuring the real-time and best-effort traffic delays, obtained with the protection method, are presented and evaluated. The effectiveness of the mechanism is demonstrated, since the delay experienced by real-time traffic is below required limits. Also the delay for best-effort traffic is not really affected by the application of the protection mechanism.**

Index terms: Optical Packet and Circuit Switching, integrated hybrid networking, component-level protection, availability.

I. Introduction

Future networks are expected to support a wide range of applications and services, with different requirements to Quality-of-Service (QoS). Optical networks are envisioned as the paradigm for future networks, as they provide high bandwidth and adequate flexibility, when properly managed.

Currently, two main switching alternatives proposed for future optical networks are Optical Packet Switching (OPS) and Optical Circuit Switching (OCS). OPS is regarded as one of the best alternatives [1], achieving high utilization of resources through statistical multiplexing (SM) of packets. However, OPS networks experience packet loss and high processing requirements in intermediary nodes. In OCS circuits are established between ingress and egress nodes, thus hardware requirements in core nodes are relatively low. However, such circuits could lead to low utilization of resources when traffic sources are bursty [1].

In general, it is considered that combining OCS and OPS in the same infrastructure may achieve cost and performance benefits [2]. Several hybrid OPS/OCS networking schemes [3], [4] have been presented as possible architectures for future optical networks. One of the most recent is the 3-Level Integrated Hybrid Optical Network (3-LIHON) [5]. The 3-LIHON concept is based on the Optical Migration Capable Network with Service Guaranties (OpMiGua) [4], and its extension employing Optical Codes (OCs) [6]. 3-LIHON, as a possible solution for all-services integrated network architecture, must be provided with its own protection mechanisms. Indeed such networks must achieve adequate survivability, i.e. the ability of a network to continue providing transport services in the presence of failures. This is a crucial QoS aspect in next-generation optical networks.

To design a highly survivable network, at least three layers suitable for dependability mechanisms can be distinguished [7]: component redundancy, node redundancy and network redundancy. The relation and comparison between the three levels of dependability have been a subject of discussion over the last years [8]. Although dependability methods deployed in higher layers are more comprehensive, their response times are slower than those of lower layer dependability mechanisms [7]. Hence node and component redundancy have gained importance because of their fast recovery from failures [9].

This article proposes a component-level protection mechanism for the real-time traffic in the 3-LIHON node architecture. In particular the protection mechanism does not require additional hardware since it exploits the intrinsic feature of the 3-LIHON node, consisting of different switching subsystems. An availability analysis is also presented taking into account the protection mechanism proposed. Simulation results are presented for checking the performance in case the protection mechanism is applied, showing how the delay for real-time traffic can be kept under acceptable values.

This paper is organized as follows. Sect. II describes the 3-LIHON architecture and its functionalities. Sect. III presents the local protection mechanism developed for real-time traffic. Sect. IV introduces the availability analysis of this mechanism. Sect. V compares the delays obtained in normal situation and when applying the proposed protection scheme due to a failure. Finally Sect. VI gives the conclusions of this work.

II. The 3-LIHON architecture

This section presents the main features of the 3-LIHON architecture. This description aims at presenting the node architecture for understanding the protection techniques described in the next sections. A comprehensive description of the 3-LIHON network concept and node functionalities can be found in [5].

In the 3-LIHON network, three transport services are considered in order to meet the requirements of current and future network services. A possible mapping of those network services in the transport classes is presented in [5]. The three transport services are Guaranteed Service Type (GST), Statistically Multiplexed Real Time (SM/RT) and Statistically Multiplexed Best Effort (SM/BE). The three traffic types related to the transport services are time multiplexed in the wavelengths of the optical links. Hence the wavelengths are shared among the traffic types.

The 3-LIHON node architecture able to manage these transport classes is sketched in Fig. 1, as in the case N input/output fibers carrying M wavelengths. Since the traffic

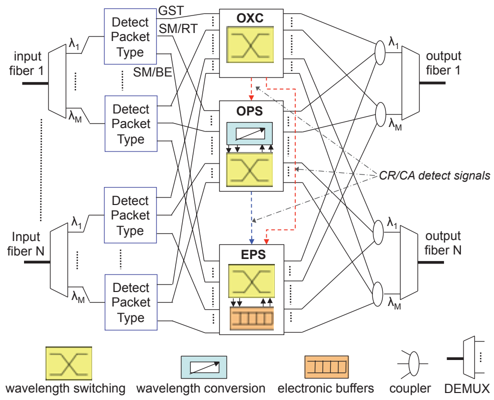

Fig. 1. General scheme of a 3-LIHON node.

types are time multiplexed in the network wavelengths, a Detect Packet Type (DPT) subsystem is needed on input to identify the transport class of an incoming packet. Each input wavelength is supplied with a DPT subsystem. The DPT is in charge of identifying the transport class of an incoming packet and routing it accordingly. Different implementations for the DPT can be considered, for example those presented in [4], [6]. In this study we assume the use of OCs in the DPT, as described in [5], [6]. In particular different OCs are assigned to the three traffic types. OCs are attached in front of the optical packets as labels. When a packet arrives at the DPT, the optical label is sent to an OC decoder [6], which identifies the class the packet belongs to and forwards it to the proper switching subsystem.

Indeed the core of the node consists of three switching subsystems: i) an Optical Cross-Connect (OXC); ii) an Optical Packet Switch (OPS); iii) an Electronic Packet Switch (EPS). The GST bursts travel through the OXC following virtual optical end-to-end circuits, similarly to what happens in OCS networks. This way the GST traffic class provides no packet loss, limited delay, and no jitter inside the network. GST traffic is best suited for applications and services with high bandwidth demands, like video-streaming, video-conferencing or even high-quality music streaming. A GST burst will normally consist of multiple packets sent to the same destination. The SM/RT transport class is an optical packet switched service with contention for bandwidth, handled by an OPS. This class is intended for applications generating valuable traffic though in low volumes (transported as short packets), requiring real-time service and tolerating moderate packet loss. Due to these requirements, GST class is not suitable for this kind of traffic. An OPS without buffering is the best switching option for this type of traffic. It achieves zero-delay (no buffering, no O/E/O conversion), while packet loss is tolerated. SM/RT is best suited for services like traffic control (i.e. signaling and routing information) and Voice-over-IP. Finally, SM/BE transport class is also an optical packet switched service managed by an EPS. The EPS is equipped with electronic buffers, hence SM/BE packets experience O/E/O conversion at every node. SM/BE is the lowest priority traffic class, so there is no guaranteed delay in the EPS. Thus it is not suited for real-time traffic as the EPS will introduce additional delay (O/E/O conversion, buffering). SM/BE is best suited for data transfer and for interactive messaging with low real-time demands.

According to Cisco's predictions, all forms of video (carried by GST and SM/BE traffic classes) will account for close to 90% of all consumer traffic by 2015 [10]. Thus, GST and SM/BE traffic classes are expected to carry the largest traffic volumes while SM/RT traffic will represent a small, though important, amount of the traffic. This allows to keep the OPS small and simple. By means of different methods (e.g. concentrators [11]), the number of input ports at the OPS could be reduced; thus reducing the cost of such an element. 3-LIHON achieves a high throughput efficiency by statistically multiplexing SM/RT and SM/BE packets in voids among GST bursts. The OPS and EPS are also in charge of attaching the proper OC label in front of the outgoing packets.

In order to manage collision avoidance (CA) among packets in different classes and contention resolution (CR) among packets in the same class, detect signals are exchanged among the switching subsystems. For CA: i) GST bursts are provided with maximum priority. They have non-preemptive priority over SM/RT packets and preemptive priority over SM/BE; ii) SM/RT packets have preemptive priority over SM/BE packets. The non-preemptive priority of GST over SM/RT is obtained by letting the GST bursts through a fixed length Fiber Delay Line (FDL), with fixed delay (D_{GST}) equal to the maximum SM/RT packet duration. This way an SM/RT packet in transmission is never interrupted by an incoming GST burst. Same way, when the EPS detects an incoming GST burst, its current transmission can continue for a time D_{GST}. This is useful for the protection mechanism, as described in Sect. III.

For CR: i) the OPS solves it by wavelength conversion, but it does not consider output channels where GST bursts are in transmission; ii) the EPS solves it by buffering and wavelength selection (using tunable lasers) in the electronic domain, but it does not consider output channels where GST or SM/RT packets are in transmission.

III. Protection mechanism

In this section, a local protection mechanism for the SM/RT transport class is presented. This traffic class has to be protected because it carries control traffic (signaling and routing information), thus affecting the other traffic classes. The main idea consists in using the EPS employed for SM/BE traffic as backup for the OPS. This protection mechanism not only improves the availability of SM/RT connections, but also takes advantage of the structure of a 3-LIHON node.

Fig. 2 illustrates the physical protection scheme. The EPS and the DPT are the two components needed to deploy this protection scheme. Thus, no additional components are needed to implement it. The DPT subsystem reroutes SM/RT packets

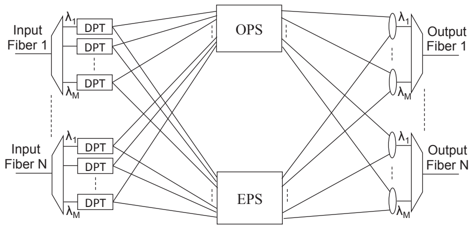

Fig. 2. Physical scheme for rerouting SM/RT traffic to the EPS.

to the EPS if a failure in the OPS is detected. Failures in the OPS can be detected by monitoring the optical signal at the outputs of the OPS. Upon failure detection, the DPT is signaled, so that incoming SM/RT packets are sent to the EPS. This can be easily implemented in the DPT with additional logical functionalities. No additional hardware is required. In the EPS, as SM/RT packets have real-time requirements, they are provided with non-preemptive priority over SM/BE packets in the electronic buffer. The only additional feature to be added to the EPS is that at its output, not only SM/BE but also SM/RT OCs must be attached to the corresponding packets. The EPS must be able to access the routing information regarding SM/RT packets. A unified control plane for the three traffic classes could deal with the problem.

It is important to notice that SM/RT packets will not be interrupted by GST bursts even when they are handled by the EPS. As introduced in Sect. II, the EPS continues sending the current packet for a time D_{GST} (max. SM/RT duration). Thus, any current SM/RT packet being sent by the EPS will be completely transmitted before the GST transmission begins.

The fact that this restoration mechanism does not need additional components, compared to similar local protection mechanisms [9], implies some important advantages. First, it can be regarded as an almost zero-cost mechanism. There is no need for additional optical switches to reroute the traffic, as in [9] for example. In addition, this mechanism is able to achieve fast restoration times because the time needed to reroute the traffic to the EPS is basically equal to the time needed to detect the failure of the OPS, plus the time needed to signal the DPT subsystem. Last but not least, the energy consumed is the same as in a normal operation situation, as no spare components must be put into operation.

Even though some packets could be lost during the take over, it will not affect significantly the service delivery and can be considered as packet loss within the OPS during normal operation. However, as the EPS will handle both types of SM

TABLE I

COMPONENTS NOTATION AND AVAILABILITY FIGURES.

Component	Notation	Availability	Reference
Mux - Demux	A_{mux}, A_{demux}	0.9999952	found in [12]
DPT	A_{DPT}	0.999976	calc. as in [14]
OPS	A_{OPS}	0.995	calc. as in [14]
EPS	A_{EPS}	0.999816	calc. as in [14]
Coupler	$A_{coupler}$	0.9999999	found in [13]

traffic, it is important to keep track of the QoS degradation. Delay of SM/RT packets, that are now converted to the electronic domain and stored in a buffer, plays a major role. It has to be kept under acceptable values for applications with real-time requirements. SM/RT traffic is expected to represent a small percentage of the total load, and in this case the delay experienced by SM/RT packets can be kept under adequate values, as presented in Sect. V.

IV. AVAILABILITY ANALYSIS

This section presents the availability analysis, performed by means of a reliability block diagram, of the protection scheme presented in Sect. III.

In this analysis, the availability of an SM/RT traffic stream crossing a 3-LIHON node is calculated. In the case of study, the SM/RT traffic stream is defined as a logical connection through the node, arriving at one particular wavelength on one particular fiber. However, this traffic stream is due to leave through one particular fiber, but any outgoing wavelength still working is available for use. This implies that a node is capable of locally detecting failed outgoing wavelengths.

The notation for the different components, as well as the availability figures for each of them, are shown in Tab. I. Availability of mux/demux and couplers is taken from [12] and [13] respectively. DPT, OPS and EPS availabilities have been calculated employing the method described in [14].

It is possible to model the system, with respect to service availability, employing a reliability block diagram. The diagram is depicted in Fig. 3 for one SM/RT flow, following the next considerations. First, independent failure probabilities are assumed for all components. It is also assumed that any failure in a packet switch is captured by failure of the core component of that switch. In addition, failures in the output couplers multiplexing the three traffic types can be notified to the switch control, in order not to consider that output wavelength as available. Then, the OPS and the EPS form a parallel structure from a dependability point of view, and the same can be applied to the M output couplers. By defining the

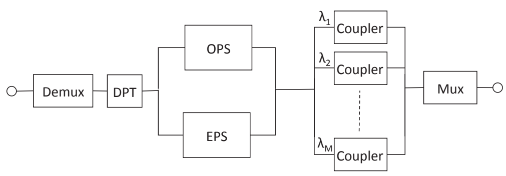

Fig. 3. Reliability block diagram for the proposed protection mechanism.

availability of the parallel OPS-EPS block structure as

$$A_{OPS-EPS} = (1 - ((1 - A_{OPS}) * (1 - A_{EPS}))) \quad (1)$$

and the availability of the pool of M parallel couplers as $A_{pcoupler} = (1-(1-A_{coupler})^M)$, the asymptotic availability follows equation (2):

$$A = A_{demux} * A_{DPT} * A_{OPS-EPS} * A_{pcoupler} * A_{mux} \quad (2)$$

To assess the availability that can be attained by an SM/RT flow with this protection mechanism, a sensitivity analysis has been performed using Matlab. The results are presented in Fig. 4 assuming M=32 output wavelengths. The asymptotic unavailability (U=1-A) attained by the system when the values presented in Tab. I are employed is $3.415 * 10^{-5}$. This value is plotted in Fig. 4 with a line marked with circles and labelled as reference. The other lines depict the variation of the total unavailability as a function of the unavailability of one component at a time (from 10^{-7} to 10^{-2}). The other unavailabilities remain fixed and can be found directly from the values of Tab. I.

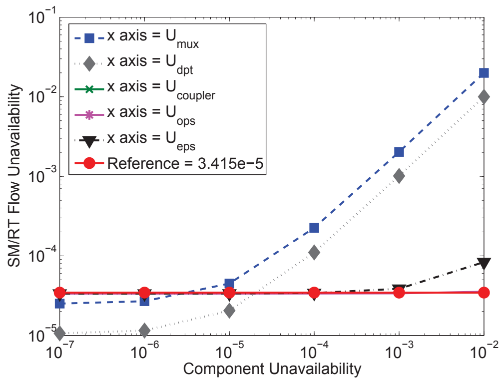

Fig. 4. Unavailability results of the proposed protection mechanism.

In Fig. 4, the influence of varying the unavailability of couplers and the OPS is not visible. The lines corresponding to these two components are hidden behind the reference line. The unavailability of an SM/RT flow is not influenced even if the unavailability of these components is very high. Couplers are reliable elements, as they are simple passive devices. In addition, the M output couplers form a parallel structure from the reliability point of view, resulting in a very high availability for the subsystem made up by these M couplers. The OPS is a less reliable element, but as it is backed up by the EPS, it has not a severe impact on the total unavailability.

The EPS does not compromise the total unavailability of an SM/RT traffic stream unless its unavailability figure presents a value over 10^{-3}. Indeed the SM/RT traffic exploits the OPS when this is still working. The EPS mainly relies on mature, already mass-produced technology. In fact, it can be regarded as an electronic router with electronic buffering, provided with O/E/O conversion. Because of that, the EPS can be expected to achieve unavailability figures far below 10^{-3}, and thus not representing a risk for the total unavailability.

Instead multiplexers/demultiplexers and the DPT subsystem could become a serious problem for the total unavailability of an SM/RT flow. As shown in Fig. 4, the asymptotic unavailability of the system highly depends on these two components. Multiplexers and demultiplexers are simple passive devices, usually with low unavailability figures. The DPT subsystem is the actual bottleneck for the availability of an SM/RT flow. Indeed the DPT is based on Optical Codes, and this technology is regarded as very promising, but nowadays it can only be found in laboratories as a prototype. The availability value assumed for the DPT subsystem in Tab. I has been calculated employing the method described in [14], being only an approximation. Although most of the DPT components are passive devices, it is not unrealistic to consider the DPT subsystem as a likely to fail element, with a high unavailability value. What is more, the DPT subsystem handles the three types of traffic considered in 3-LIHON, and could compromise the availability of all types of connections. Hence, the DPT subsystem can be considered as the most sensitive part for achieving high reliable SM/RT flows in the 3-LIHON architecture. It can be protected by providing spare DPTs in the nodes. It is important to remember that when a DPT fails, just one SM/RT flow is affected (as well as one GST and one SM/BE), while the other SM/RT flows traversing the node are not affected.

V. Simulation results

This section presents simulation results for both normal and failure operation (the OPS fails and the protection mechanism is applied). Results present the delay of both SM/RT and SM/BE traffic types. Here we consider additional delays related to the wavelengths' utilization in 3-LIHON nodes. Other constant delays in the EPS (e.g. those for O/E/O conversion) are not considered. Those delays should be added to the results presented in this section to assess the total delay. Here the focus is put on those delays related to the buffering in the EPS. As SM/RT packets, there is no delay in normal operation, since the OPS does not provide buffering. SM/RT packets could experience delay due to GST traffic in failure mode. SM/BE packets could experience delay due to both GST and SM/RT traffic in normal and failure modes. The average and maximum delay have been measured when the protection mechanism is applied, meaning SM/RT packets managed by the EPS. For SM/BE packets, a comparison between the SM/BE delay experienced in normal and failure operation is presented.

The simulator has been implemented using the Simula-based discrete-event simulation tool DEMOS. GST traffic travels across the OXC in virtual circuits, with no loss and small fixed delay D_{GST}, and it is not influenced by the SM/RT and SM/BE traffic. SM/RT and SM/BE exploit the remaining available bandwidth. As explained in Sect. III, SM/RT packets cannot be interrupted by GST bursts, neither in normal nor in protection regime, thanks to the delay D_{GST} the latter experience. As SM/BE packets, in normal operation they can be interrupted by both GST and SM/RT. In the OPS failure operation SM/BE packets can be interrupted by GST but not by SM/RT packets. Indeed SM/RT and SM/BE packets are both managed by the EPS and the former have non-preemptive priority with respect to the latter. The results presented here verify that this decision is better suited, in terms of delay performance, than letting SM/RT packets preempt SM/BE traffic within the EPS. The buffers use a first-come-first-served policy within the same SM traffic type. When an SM/BE packet is interrupted, we consider it reenters the buffer in the last position. The EPS is assumed to be a cut-through switch, entailing lower delays. Here we focus on the achieved delay, so buffers of infinite length have been assumed. Hence there is no loss for SM/BE traffic in normal and failure operation, and no loss for SM/RT packets in failure operation.

Packet delay is computed in a single output fiber with 32 wavelengths. 32 independent generators, with negative exponential distributed arrival times, for each type of traffic are employed as input. The packet lengths are also negatively exponentially distributed, with a mean value of 625000 bits for GST, 555.6 bits for SM/RT, and 20000 bits for SM/BE packets. A maximum length for SM/RT packets is assumed, in order not to generate large SM/RT packets. The maximum length of an SM/RT packet is 2778 bits (5 times the mean value). These values were chosen in accordance with values employed in previous simulations of 3-LIHON [5]. Results were calculated with a 95% confidence level. Error bars (95% confidence intervals) are within the marker points and not plotted for the sake of clarity.

Fig. 5 presents the average and maximum delay (in ns) experienced by SM/RT packets in the failure situation. Delays are plotted as a function of the relative percentage of GST traffic, for different total loads. SM/RT traffic is assumed to be a small percentage, thus it is fixed to represent 7% of the total load. The remaining percentage of the traffic is SM/BE, varying in accordance with the relative GST percentage.

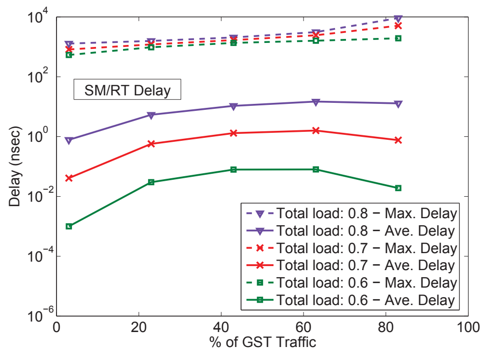

Fig. 5. SM/RT delay in failure situation, as a function of the percentage of GST with respect to the total load. SM/RT traffic is 7% of the total load.

Let's focus first on the average delay. The average delay experienced by SM/RT traffic increases significantly when the total load increases. As the effect of the percentage of GST traffic, typically the SM/RT average delay increases when GST traffic grows (and SM/BE traffic decreases). This is because more bandwidth is occupied by GST traffic, so there are fewer and smaller voids in between GST bursts for forwarding SM/RT and SM/BE packets. However, if the relative GST load is very high (83%), the SM/RT average delay decreases. The explanation is that the output wavelengths are mainly being used by GST traffic, while SM/BE traffic represent a small percentage of the total traffic (10%). Consequently, SM/RT packets in the electronic queues do not have to wait a long time for SM/BE packets to finish their transmission, and the delay decreases. This trend is more evident for low loads (0.6) than for high loads (0.8). Thus, for high loads, the delay does not vary substantially when the relative percentage of GST traffic is larger than 40% of the total traffic. Low loads imply smaller delays, but then this delay may vary significantly depending on the relative percentage of GST and SM/BE traffic.

About the maximum delay, Fig. 5 points out that it is reasonable even for applications with strict real-time requirements. In general, the maximum delay increases with the relative percentage of GST traffic, and with the total load. This is due to the same reasons previously explained for the average delay. For high loads (0.7 and 0.8), the trend is more pronounced when the relative percentage of GST traffic is high. However, even with high loads (0.8) and a high percentage of GST traffic (83%), the maximum delay is below 10 μs.

Fig. 6 compares the average delay experienced by SM/BE packets in normal operation and in case of OPS failure. The

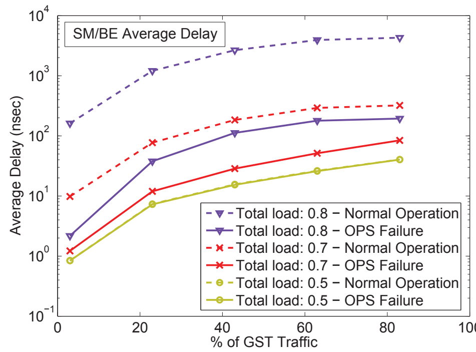

Fig. 6. Average SM/BE delay in normal and failure operation, as a function of the percentage of GST traffic. SM/RT traffic is 7% of the total load.

SM/BE delay is presented as a function of the relative percentage of GST traffic, for different loads. The delay is evaluated including SM/BE retransmissions due to interruptions by GST and SM/RT (the latter in normal operation only). Hence, the delay is evaluated as the difference between the time the packet is successfully transmitted and the time it entered the queue for the first time. Consequently, the number of retransmissions may severely impact the delay. SM/BE delay increases with the total load and with the percentage of GST traffic. This means that less relative percentage of SM/BE traffic implies larger SM/BE delays. Basically, this is because as the percentage of GST traffic increases, SM/BE packets are interrupted more, reentering the buffer several times. For low total load (0.5), SM/BE delay is the same for normal operation and OPS failure. However, the delay experienced by SM/BE packets when the total load is high (0.7 and 0.8) is much larger in normal operation. This is because in normal operation, SM/BE packets can be interrupted not only by GST burst but also by SM/RT packets. If the total load is high, even though SM/RT is just 7% of the total load, there is a large number of small SM/RT packets to be transmitted. These small SM/RT packets often interrupt SM/BE packets in transmission. Thus a relevant number of SM/BE packets experience higher delays due to retransmissions. Instead in the failure operation, SM/RT packets do not interrupt SM/BE, so delays are smaller. Anyway, in both operation modes, delays are below 10 μs, and SM/BE packets do not have any strict delay requirement.

Finally Fig. 7 compares the SM/BE maximum delay in the two situations. It illustrates how the trend is almost the same

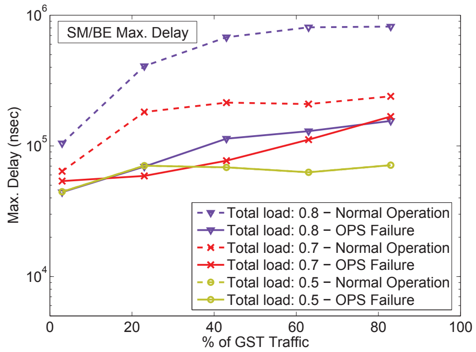

Fig. 7. Maximum SM/BE delay in normal and failure situation, as a function of the percentage of GST traffic. SM/RT traffic is 7% of the total load.

as for the average delay. Even in this case the delay is higher for the normal situation, and it becomes relevant when the total load is high (0.8). Still it is bounded below 1 ms.

Even assuming that SM/RT packets do not experience any delay in normal operation, the simulation results show that SM/RT packets experience tolerable average and maximum delay for real-time applications in failure situation. Furthermore, the delay experienced by SM/BE packets in failure mode is equal or even lower than that in normal operation. Thus, the proposed protection mechanism is effective in protecting SM/RT and does not have a significant impact on the QoS of the traffic types. It should be noted that although the delays are kept under tolerable values, the EPS cannot be used for carrying SM/RT traffic in normal operation. If the EPS is used in normal operation for both SM/RT and SM/BE classes, SM/RT packets will experience additional delays (O/E/O conversion, buffering) in every node. Then, SM/RT traffic class could not fulfill the requirements for real-time traffic. The delays presented in this section are tolerable because SM/RT packets experience them only in one node (the failed one).

VI. Conclusions

This paper presented a protection mechanism for the SM/RT traffic service provided by 3-LIHON. By exploiting the EPS and the flexibility inherited from the DPT in packet detection, this mechanism is able to achieve high availability for SM/RT traffic connections, without degrading the expected QoS for this type of traffic. This is of extreme importance as SM/RT packets carry control traffic, which manages the set-up and tear-down of GST end-to-end circuits, as well as routing information and network layer dependability mechanisms. In addition, the QoS required by the other traffic types is also met. Achieving an unavailability almost equal to the 10^{-5} unavailability figure, this protection scheme does not need the deployment of additional components inside a node. Thus, it reveals itself as an inexpensive, energy-efficient mechanism, capable of attaining fast restoration times.

Simulation results demonstrates the feasibility of this mechanism, keeping the delay experienced by SM/RT packets below acceptable values for applications with strict real-time requirements. However, the availability bottleneck that the DPT subsystem represents calls for further research on how to increase the availability of this subsystem. Furthermore, the proposed solution requires a study of the packet loss for SM/RT and SM/BE when limited buffers are considered, with the purpose of allowing a proper buffer dimensioning.

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