# A Novel Restoration Algorithm Based on Optical Signal-to-Noise Ratio for Transparent Optical Networks

Rodrigo C. de Freitas, Rodrigo C. L. Silva, Helder A. Pereira, Daniel A. R. Chaves, Carmelo J. A. Bastos-Filho
and Joaquim F. Martins-Filho

*Abstract*— **In this paper, we propose a novel algorithm to restore calls upon a single failure in transparent optical networks. After a failure, the proposed algorithm performs a path restoration searching for the route which presents the higher optical signal-to-noise ratio. We compared our proposal to three other well known approaches in the literature. We achieved lower failure rates in the restoration process for three different scenarios.**

*Keywords*— **Survivable Optical Networks, Transparent Optical Networks, Path Restoration, Physical Impairments.**

## I. INTRODUCTION

Transparent optical networks have been considered as the most reliable and effective solution to achieve high transmission capacities for long haul distances with relative low cost. In these networks, the signal remains in the optical domain between the edge nodes, *i.e.* the signal propagates through the core nodes of the optical network without any optical-electrical-optical (O/E/O) conversion [1]. These networks are also often called all-optical networks.

There are two main challenges to manage all-optical networks providing a minimum predefined quality of service (QoS): (1) design an appropriate routing and wavelength assignment algorithm (RWA) and (2) obtain an acceptable optical signal-to-noise ratio (OSNR) at the destination node in order to reach an appropriate quality of transmission (QoT) for every optical signal [1], [2]. These requirements should also be considered to tackle the survivability problem in optical networks, *i.e.* the optical signal degradation has to be taken into account on the search for spare resources (alternatives routes and free wavelengths) [3].

In a wavelength-routed optical network (WRON), a failure in a network element can cause the failure of several lightpaths, thereby leading to large data and revenue losses [3]. Therefore, all-optical networks should be fault tolerant in order to avoid service interruption. Some example of possible devices subjected to failures are: ports on a client equipment, optical-layer hardware, fiber link and crossconnectors. As main causes of failures, one can mention [4]:

- Human error: a backhoe operator accidentally breaks an optical cabling.
- Fault equipment: bad functioning of transmitters, receivers or controllers.
- Natural disasters: flood, earthquake or fire can cause a complete interruption of service from one provider.

Connection availability is a critical factor to providers. A common requirement for commercial systems is an availability of $99.999\,\%$ of the time, which corresponds to a downtime of less than $5$ minutes per year [4]. The only practical alternative to ensure this availability is to provide survivable mechanisms which guarantee the continuity of services in the case of faults. There are two main survival schemes for optical networks. The first is called protection, when backup resources (routes with free wavelengths) are pre-computed and reserved in advance. These resources remain dedicated for the protection purpose during the network operation. In protection scheme, the network resources may be dedicated for each failure scenario. The other scheme is called restoration, which is responsible to discover dynamically another route with a free wavelength for each disrupted connection [3]. In dynamic restoration scheme, the spare capacity available within the network is utilized for restoring services affected by a failure. Generally, dynamic restoration schemes are more efficient in utilizing capacity due to the multiplexing of the spare-capacity requirements and provide resilience against different kinds of failures, while protection schemes are faster in terms of time and provide guarantees on the restoration ability [5].

There are two approaches to the dynamic restoration scheme [5]:

- **Link restoration** - in which the end nodes of the failed link participate in a distributed algorithm to dynamically discover a route around the link. If no routes are available for a broken connection, then the connection is dropped.
- **Path restoration** - in which the source and destination nodes of each connection traversing the failed link participate in a distributed algorithm to dynamically discover an end-to-end backup route. If no routes are available for a broken connection, then the connection is dropped.

In this paper, we focus on path restoration scheme and we propose a novel algorithm to restore calls upon a single failure in transparent optical networks considering physical layer impairments. The proposed algorithm searches for the backup route with the higher OSNR. The analytical model

Rodrigo C. de Freitas and Joaquim F. Martins-Filho are with the Department of Electronics and Systems, Federal University of Pernambuco, Recife, Pernambuco, Brazil, 50740–530, E-mails: {rodrigo.choji, jfmf}@ufpe.br
Rodrigo C. L. Silva, Daniel A. R. Chaves, Helder A. Pereira and Carmelo J. A. Bastos-Filho are with Polytechnic School of Pernambuco, University of Pernambuco, Recife, Pernambuco, Brazil, 50720–001, Emails: rcls@ecomp.poli.br,{daniel.chaves, helder.pereira, carmelofilho}@poli.br

used for evaluating the OSNR for each lightpath was proposed by Pereira *et al.* [6]. We have considered the effect of gain saturation and amplified spontaneous emission (ASE) noise depletion in amplifiers, coherent crosstalk in optical switches, four wave mixing (FWM) and polarization mode dispersion (PMD) in optical fibers as physical impairments that cause QoT degradation in the optical signals to validate our proposal.

The rest of the paper is organized as follows: Section II presents some previous works proposed to solve the survivability problem in optical networks. In Section III, we describe the OSNR model and we detail the physical layer effects considered in this paper. In Section IV, we present the main concepts about survivable optical networks, the methodology used to validate our proposal and the novel restoration algorithm based in OSNR. In Section V, we describe the simulation setup. In Section VI, we show the simulation results for the analysis of the failure rate. In Section VII we give our conclusions.

## II. LITERATURE REVIEW: PATH RESTORATION APPROACHES

The survivability problem in optical networks has been investigated since the early 90 [7], [8], but the interest of researchers in this theme have grown over the past two decades. In particular, several restoration strategies have been proposed. One of the first papers addressing systematically the survivability in optical networks strategies was developed by Ramamurthy *et. al* [5], in which they analysed the strategies of protection and restoration in optical networks. With the evolution of this issue, novel and efficient techniques were developed to ensure the traffic restoration. Pavani *et. al* [9] proposed a single fault-tolerant dynamic routing and wavelength assignment (RWA) algorithm based on the ant colony optimization (ACO). Because of the distributed control of the network, the dynamic nature of the traffic and the unpredictability of a failure event, the flexibility and robustness of ACO make it a suitable candidate for provisioning lightpaths in an optical network. Eiger *et. al* [10] presented a design algorithm for networks with a restoration mechanism which provides a failure independent end-to-end path protection to a set of given demands under a single link or node failure. The restoration routes are provided on preconfigured cycles (p-cycles), where each of the demands is assigned to a single restoration route and specific restoration wavelengths on a segment of one cycle. Currently, the effects of physical layer impairments have been considered for solving the survivability problem because of the huge demand for data, the high transmission rates and the long distances. Therefore, an efficient strategy to find an alternative lightpath must also check whether this new lightpath has an acceptable QoT as well [11].

## III. OSNR DEGRADATION

All-optical networks generally operates with high transmission capacities and the signal remains in the optical domain between the edge nodes, *i.e.* the signal propagates along the core of the optical network without any optical-electrical-optical conversion. Because of the linear and nonlinear physical layer effects in optical fibers and the additive noise inserted by the network elements along the lightpaths, the OSNR of the transmitted signal can be mitigated, which have directly impact on the QoT [6].

The impact of physical layer impairments is taken into account by considering the signal power and the noise power at the destination node, both affected by gains and losses along the lightpath. Moreover, some network elements add noise components or have a nonlinear response. As examples, we can cite: the optical amplifiers add ASE noise power and are also affected by gain saturation and ASE depletion as the total input signal power increases. The optical switches add noise due to non-ideal isolation between ports. The transmission fibers add noise due to FWM when the signal wavelength is close to zero dispersion wavelength ($\lambda 0$) and also induce pulse broadening due to (PMD) [6].

In this paper, we used an analytical model based on OSNR degradation to take into account the effect of gain saturation and ASE noise depletion in amplifiers, coherent crosstalk in optical switches, FWM, and PMD in optical fibers, proposed by Pereira *et. al* [6]. It considers these effects all together and it uses simple analytical equations obtained from well known fundamental or experimental behavior of network devices [6]. In this work, we neglected the effect of FWM since it takes a long time to be evaluated and is not crucial to demonstrate that our proposal is suitable to solve the survivability problem.

## IV. OSNR-ROUTING (OSNR-R) RESTORATION ALGORITHM

Dynamic restoration schemes have to discovered dynamically an alternative lightpath for each interrupted connection [12]. However, until this moment, all the previous approaches use the shortest path or the minimum number of hops to search these alternative lightpaths. We propose in this paper to search dinamically for the lightpath with higher OSNR. We believe this can allow to simultaneously find good routes in terms of QoT and distribute load along the network. Simple algorithms to balance the load such as least resistance weight (LRW) could be applied. However, we observed that this algorithm often finds routes that are too long to maintain the QoT.

We used the following methodology to implement our approach: (1) we studied the network stability in relation to the use of its resources in order to define when the network achieves the steady state; (2) we freeze the network state in order to realize the fault simulations in a realistic scenario. Given the frozen state of the network, we remove one link at a time and apply the restoration algorithm 1 attempting to recover the calls which were passing through it. A call is considered restored when there is wavelength and path availability and the physical layer impairments are below a threshold value. We do these simulations for every link in the network.

## V. SIMULATION SETUP

We tested and compared our proposal (OSNR-R restoration algorithm) to three well known metrics to find the restoration

**Algorithm 1** New Approach for Path Restoration

```
1: for every link of the network do
2:     Identify the calls which pass by the link;
3:     Create a copy of the network in the stable state;
4:     for every call that passes through link do
5:         Set free the occupied lightpaths which pass by the link;
6:     end for
7:     Simulate link failure;
8:     for every call that passes through link do
9:         Search for an alternative route considering higher OSNR-R;
10:        Evaluate wavelength and path availability;
11:        Evaluate physical layer impairments;
12:        Count quantity of recovered calls;
13:    end for
14:    Calculate link failure rate;
15: end for
```

TABLE I

DEFAULT SIMULATION PARAMETERS.

| `Parameter` | `Value` | `Definition` |
|---|---|---|
| $P_{sat}$ | 26 dBm | `Amplifier output saturation power.` |
| $OSNR_{in}$ | 40 dB | `Input optical signal-to-noise ratio.` |
| $OSNR_{QoS}$ | 23 dB | `Optical signal-to-noise ratio for QoS criterion.` |
| $B$ | 40 Gbps | `Transmission bit rate.` |
| $B_o$ | 100 GHz | `Optical filter bandwidth.` |
| $\Delta f$ | 100 GHz | `Channel spacing.` |
| $\lambda_i$ | 1529.56 nm | `The lower wavelength of the grid.` |
| $\lambda_0$ | 1557 nm | `Zero dispersion wavelength.` |
| $\alpha$ | 0.2 dB/km | `Fiber loss coefficient.` |
| $L_{Mux}$ | 2 dB | `Multiplexer loss.` |
| $L_{Demux}$ | 2 dB | `Demultiplexer loss.` |
| $L_{Switch}$ | 2 dB | `Optical switch loss.` |
| $\delta$ | 10% | `Maximum pulse broadening.` |
| $W_{MIN}$ | 4 | `Minimum number of wavelengths per link` |
| $W_{MAX}$ | 40 | `Maximum number of wavelengths per link` |
| $F_0$ `(NF)` | 3.162 (5 dB) | `Amplifier noise factor (Noise figure).` |
| $\Delta\lambda_{tx}$ | 0.05 nm | `Transmitter linewidth.` |

link: shortest path (SP), minimum number of hops (MH), least resistance weight (LRW). The procedure for the other algoritmhs is the same used in our approach as showns in algorithm 1, except for the line 9. The line 9 is substituted by: *Search for an alternative route considering shortest path*, for the SP algorithm, *Search for an alternative route considering minimum number of hops* for the MH algorithm and *Search for an alternative route considering the load distribution* for the LRW algorithm.

The topology used in this paper to perform the comparative analysis of different recovery strategies is similar to the Pacific Bell and it is shown in Fig. 1. In this version, called Modified Pacific Bell, we added two nodes, one between nodes 8 and 9 and another between nodes 5 and 6, in order to obtain links of up to 150 km and thus, avoid the use of regenerators. Table I describes the network parameters used in our simulations. For network blocking probability evaluations we used the SIMTON software, developed by Chaves *et al.* [13]

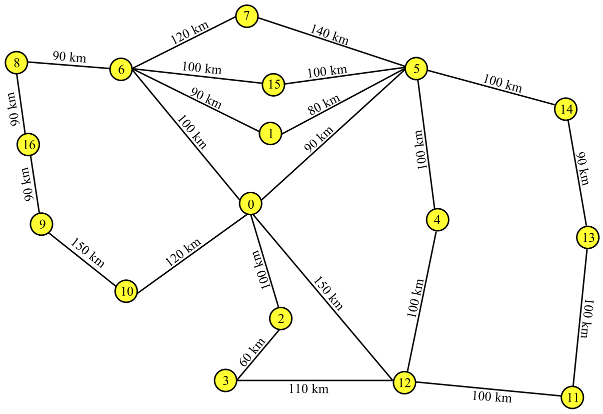

Fig. 1. Modified Pacific Bell Topology.

Initially, we analyzed the network occupation in order to identify the point at which the topology stabilizes on average use of wavelengths per link, *i.e.* we checked hom many calls are necessary for the network reaches the steady state. This investigation is important because the faults should be generated considering the steady state of the network. We believe most of failures in a realistic scenario occurs when the network is already in the steady state.

For this stability analysis, we simulated 200, 000 calls with uniformly distributed source-destination pairs and a Poisson process for three scenarios: (1) 16 wavelengths per link, as shown in Fig. 2, (2) 21 wavelengths per link, as shown in Fig. 3 and (3) 40 wavelengths per link, as shown in Fig. 4.

Table II shows the network blocking probabilities due to lack of wavelength ($BP_\lambda$) and insufficient signal quality ($BP_{QoT}$), for the scenarios 1, 2 and 3, for the network load of 60 Erlang.

TABLE II

BER BLOCKING PROBABILITY AND WAVELENGTH BLOCKING PROBABILITY FOR 16, 21 AND 40 WAVELENGTH, CONSIDERING SP, MH, LRW AND OSNR-R ALGORITHMS.

| $Qty.\lambda$ | $SP$ | | $MH$ | | $LRW$ | | $OSNRR$ | |
|---|---|---|---|---|---|---|---|---|
| | $BP_{QoT}$ | $BP_\lambda$ | $BP_{QoT}$ | $BP_\lambda$ | $BP_{QoT}$ | $BP_\lambda$ | $BP_{QoT}$ | $BP_\lambda$ |
| 16 | 0.0068 | 0.076 | 0.018 | 0.169 | 0.049 | 0.012 | 0.0044 | 0.056 |
| 21 | 0.01 | 0.012 | 0.03 | 0.084 | 0.0526 | 0 | 0.0069 | 0.0074 |
| 40 | 0.011 | 0 | 0.04 | 0 | 0.052 | 0 | 0.0079 | 0 |

Note that for the three studied scenarios, the stability of the average number of used wavelengths is reached after 200 and before 600 simulated calls.

For each scenario we chose an arbitrary point after stabilization to stop the simulation and store the network state, including the description of the active lightpaths. After that, a link is removed from the network topology, simulating a

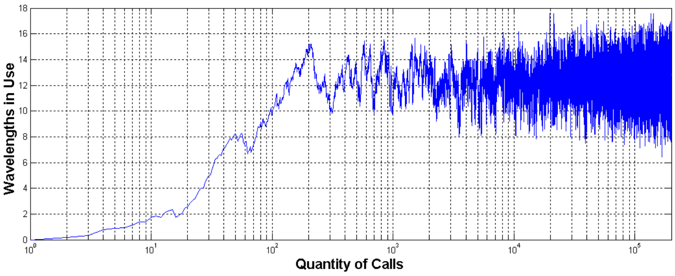

Fig. 2. Average number of used wavelengths per link as a function of the number of simulated calls, when 16 wavelengths are employed in each link.

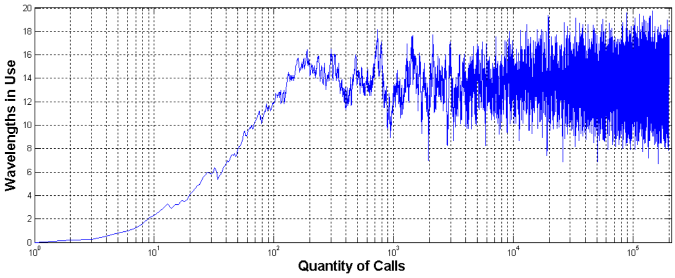

Fig. 3. Average number of used wavelengths per link as a function of the number of simulated calls, when 21 wavelengths are employed in each link.

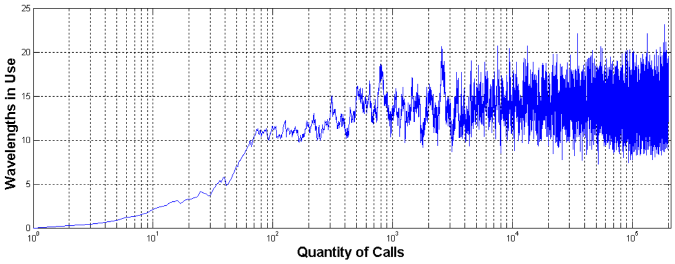

Fig. 4. Average number of used wavelengths per link as a function of the number of simulated calls, when 40 wavelengths are employed in each link.

failure. We tested the SP, MH, LRW and OSNR-R restoration algorithms to recover each of the calls that pass through the failed link. This process of link removing and search for alternatives routes is done for every link in the network.

## VI. RESULTS

We tested and compared our proposal (OSNR-R restoration algorithm) with SP, MH and LRW algorithms for the three scenarios (16, 21 and 40 wavelengths), as we mentioned on the prior section. The figures in this section show the failure rate (percentage of connections not restored) as a function of network load.

Fig. 5 shows the failure rate as a function of network load, considering 16 wavelengths. In this case, we observe that OSNR-R restoration algorithm presented a similar performance when compared to the LRW algorithm. Our proposal far outperformed the MH and the SP restoration algorithms. This behavior was expected since the failure rate and the network blocking probability are mainly due to lack of available wavelength in this scenario.

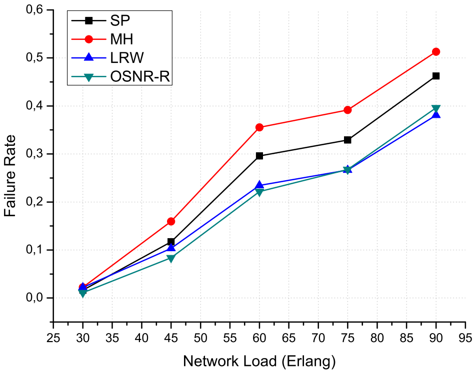

Fig. 5. Failure rate as a function of network load, considering 16 wavelengths.

Fig. 6 presents the failure rate in the scenario with 21 wavelengths per link. In this case, we have a total blocking probability around 2%, distributed in 1% of call blocking due to lack wavelength and 1% of call blocking due to physical layer impairments. Different from the previous situation, we observe that OSNR-R restoration algorithm is able to restore more connections than LRW algorithm for higher network loads.

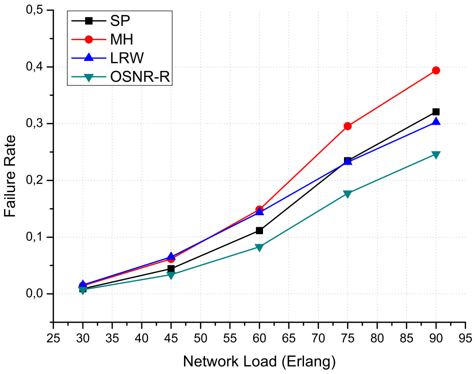

Fig. 6. Failure rate as a function of network load, considering 21 wavelengths.

Fig. 7 shows the same analysis for 40 wavelengths per link. One should notice that the blocking due to lack of available wavelengths is zero, *i.e.* the call are blocked due to the physical layer impairments. In this scenario, the OSNR-R restoration algorithm is the approach that recovers more calls again. Note that for a network with large number of wavelengths, LRW algorithm is very inefficient because it tends to distribute load along the network and does not take into account the impairments from the physical layer.

Fig. 8, 9 and 10 show the boxplot of the failure rate for the restoration algorithms considering 16, 21 and 40 wavelengths per link, respectively. For these simulations we considered 60 Erlang of network load and for the boxplot we used 50

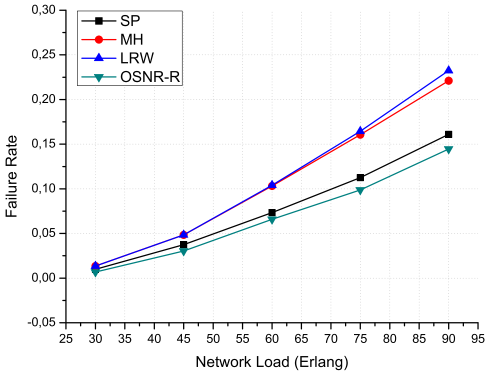

Fig. 7. Failure rate as a function of network load, considering 40 wavelengths.

simulations. In the worst case, our proposal achieved failure rate as good as the LRW approach. In the other cases, ONSR-R restoration algorithm presented lower failure rate than the other three approaches.

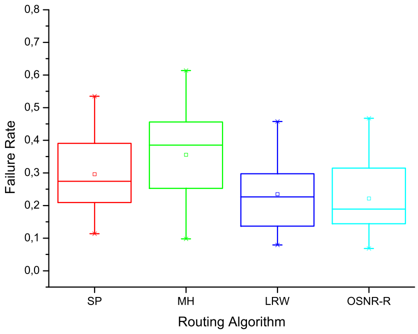

Fig. 8. Boxplot of the failure rate for the restoration algorithms considering 16 wavelengths per link.

## VII. CONCLUSIONS

We showed that the OSNR-R routing algorithm can be used to tackle the survivability problem in transparent optical networks. We presented a implementation for this restoration algorithm which takes into account the physical layer impairments to search dinamically for the alternative lightpath. It uses an analytical model which takes into account the main linear and nonlinear effects that affect the QoT of the signals. We performed simulations in three different scenarios and our proposal achieved an equal or superior performance when compared to other well known approaches in all cases.

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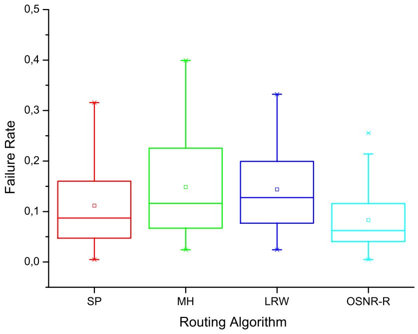

Fig. 9. Boxplot of the failure rate for the restoration algorithms considering 21 wavelengths per link.

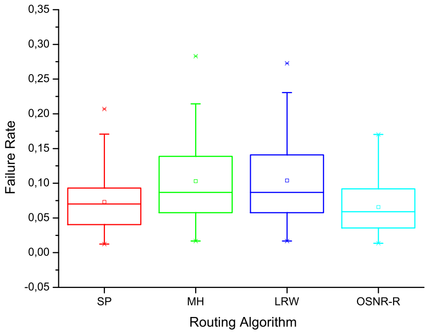

Fig. 10. Boxplot of the failure rate for the restoration algorithms considering 40 wavelengths per link.