Best Shortest Lightpath Routing for Translucent Optical Networks

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***Abstract*—This work extends for translucent optical networks the solution to the problem of finding the best choice among *M* combinations of the shortest paths. The proposed Best Shortest Translucent Lightpath (BSTL) is a novel optical routing strategy, adaptive and aware of the optical physical layer impairments. The performance of BSTL is evaluated at different scenarios (topologies, regenerator placements, impairment thresholds, etc.) using metrics like network utilization, blocking probability, and fairness. In all these scenarios, BSTL achieved a better performance that related algorithms, such as PIARA.**

Keywords – Translucent Optical Networks; Optical Physical Layer Impairment-aware Routing; Performance Evaluation.

I. INTRODUCTION

Optical networks are currently based on the Wavelength Division Multiplexing (WDM) [1] technology. WDM allows the establishment of various optical circuits (lightpaths) simultaneously in a single optical fiber using different wavelengths.

The architecture of an optical network can be classified as opaque, transparent or translucent [1]. In opaque optical networks, all nodes are opaque, i.e., each node requires Optic-Electrical-Optical (OEO) conversions of optical signals from input ports to electrical signals before processing and forwarding to output ports where electrical signals are reconverted to optical signals in order to be transmitted. Opaque nodes allow the regeneration of optical signals but the use of OEO converters insert unnecessary delays and are quite expensive. On the contrary, in transparent optical networks there are no OEO conversions at intermediate nodes of a route. In this case, optical signals are processed exclusively in the optical domain through all-optical switches. Therefore, transparent optical networks eliminate signal conversion delays at intermediate nodes of a route. In translucent optical networks, which use a hybrid approach, there are some nodes with OEO conversion capability and all others are transparent. This allows the regeneration of the optical signal along specific routes.

In practice, an optical signal is impaired when propagating through optical fiber links, optical cross-connects, optical amplifiers and other optical network elements. The accumulation of these impairments along a route, tends to increase the Bit Error Rate (BER) at the receiver, reaching prohibitive levels [2,3]. Currently, optical technologies impose the need of OEO conversions in long distance routes in order to mitigate impairments at some intermediate nodes [2]. Therefore, a new optical network architecture that uses OEO conversions at some intermediate nodes and all-optical switching in all other nodes has to be considered. Gathering features like fast switching from transparent optical networking and signal regeneration from opaque optical networking, translucent optical networking became a reality [2,3]. In this work, translucent optical networks, where opaque nodes are sparsely distributed in the network topology, is considered. Also, it is assumed the circuit-switched optical networking paradigm which means that an optical circuit (transparent or translucent lightpath) is dynamically established using network resources (wavelengths) along a route (links and nodes) between a pair of source and destination nodes.

The lightpath routing problem in circuit-switched optical networks is also known as Routing and Wavelength Assignment (RWA) [4]. RWA routing algorithms can be separated in three classes: fixed routing, alternate routing, and exhaustive routing [4].

In the fixed routing strategy, each pair of nodes (source, destination) has only one route that is previously computed. Therefore, even before a lightpath request arrival, the routing control plane already knows which route must be used for a specific source-destination pair. Normally, fixed routes are previously computed using a classical shortest path algorithm, like Dijkstra's algorithm [5] or other routing algorithms specially proposed for optical networks [6, 7, 8].

In the alternate routing strategy, a set with more than one route is previously defined for each source-destination pair. Alternate routing can be classified as fixed-alternate or adaptive alternate routing. Their differences lie in the way of selecting one route from the pre-computed set of routes. In fixed-alternate routing [4,8], the sequence of routes is

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previously defined. Routes are tried one by one in a predetermined order to establish a lightpath for a specific request. In case of failure, the lightpath request is said to be blocked. In adaptive alternate routing or adaptive routing for short [4], route selection from the pre-computed set of routes is based on the network current state. For example, one may select the least loaded route.

The exhaustive routing class algorithms have the advantage of being able to select any possible route in the topology for establishing a lightpath [4]. Therefore, in this case, a lightpath request will be blocked only if there are no routes between source and destination with at least one available continuous wavelength. However, the implementation of exhaustive routing algorithms is more complex than the implementations of the other routing classes.

This work presents a new adaptive routing algorithm for translucent optical networks, named Best Shortest Translucent Lightpath (BSTL). BSTL is inspired on the Best among Shortest Routes (BSR) proposal which optimizes the fixed routing problem in transparent optical networks [6]. But, differently from BSR, BSTL is adaptive and aware of optical physical layer impairments.

The optical physical layer impairment-aware dynamic routing problem in translucent optical networks is considered more difficult than the corresponding problem for transparent optical networks [9]. Optical physical layer impairments can be classified in two categories: linear and nonlinear. Linear impairments are independent of the optical signal power and affect each of the wavelengths individually, while the nonlinear impairments scale with optical power, affecting all wavelengths. The main linear impairments such as fiber attenuation, insertion loss, amplifier spontaneous emission, dispersion and crosstalk, are already well characterized [10]. On the other side, nonlinear impairments are more complex and difficult to characterize, needing a detailed knowledge of the optical network infrastructure. However, it is possible to adopt a simplified model where nonlinear effects are mitigated by minimizing the number of links along the lightpath [11].

Most optical signal impairments occur in function of the distance and/or the number of intermediate switches involved in the path from the source to the destination node. In this work, it is considered a hop number limit for a route without optical signal regeneration. Therefore, a lightpath must have optical signal regeneration (translucent lightpath) when it reaches a specific hop number, known as Impairment Threshold (IT) [8]. Several works in the literature adopt the hop number limitation as the main optical signal quality measure for performance evaluation of translucent optical networks [2,3,8,10,12].

In order to illustrate the Impairment Threshold concept in translucent optical networks, consider the topology example shown in Figure 1 with IT=2, which means that a route in this network will be considered feasible only if after 2 hops there is a node to regenerate the optical signal quality (regenerator node). For instance, consider the two routes (Figure 1) between a generic source-destination pair: route A and route B. Observe that while route A shows to be unfeasible because it has four hops without regeneration, on the other hand, route B appears to be feasible because after 2 hops the optical signals are regenerated (in R), reaching destination with two more hops.

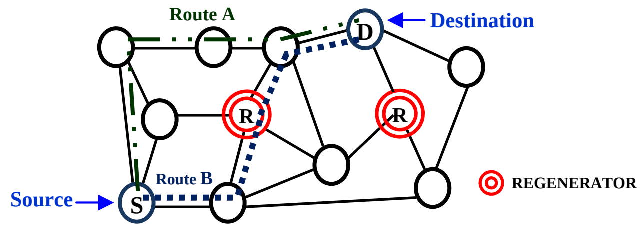

Figure 1. Example of routing in a translucent optical network.

The rest of this article is organized as follows. In Section II, previous related works are discussed. Section III introduces the shortest path selection problem for translucent optical networks. Section IV presents the new routing heuristic proposed, which performance is evaluated in Section V. Final remarks are made in Section VI.

II. RELATED WORKS

The optical signal impairment-aware routing and the wavelength assignment problems have been recently studied by many researchers [2,8,10,11,12].

In [10], one can find a survey about optical-physical-layer-aware RWA algorithms where different strategies are classified as single path or multi-path. Multi-path or multiple routes strategies search any feasible route out of *n* routes to satisfy a lightpath request. All those strategies use the shortest path algorithm for route calculation.

Rai et al. [12] proposed an information search-based algorithm for translucent optical networks that chooses feasible routes with minimal hops.

The Polynomial time Impairment Aware Routing Algorithm (PIARA) for translucent optical networks with sparse placement of regenerators is proposed in [8]. PIARA computes link costs based on optical physical impairments, and searches for feasible shortest routes passing, if necessary, through regenerator nodes. Feasible routes are obtained by means of a module based on a classical shortest path algorithm that does not use pre-computed routes. Therefore, PIARA can be considered as an exhaustive routing class algorithm.

All routing strategies used in those previous related works are based on shortest path algorithms (*e.g.*, Dijkstra`s algorithm [5]). Because they are based on or have a module implementing classical shortest path algorithms in their solutions, these routing strategies do not properly consider the case where there is more than one feasible shortest path to choose from.

In this work, we try to put in evidence this unique-best-shortest-path problem of the existing shortest path algorithms for translucent optical networks which are characterized by a reach limit for the optical signal propagation. Besides, we propose a new routing strategy for translucent optical networks, named BSTL, which main routing features are: adaptive, optical-physical-layer-impairment-aware, multiple-best-shortest-path-aware, and resource utilization efficiency.

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III. THE PROBLEM OF CHOOSING THE BEST AMONG *M* COMBINATIONS OF FEASIBLE SHORTEST PATHS IN TRANSLUCENT OPTICAL NETOWRKS

Durães et al. [6], introduced the problem of choosing the best combination among *M* Combinations of Shortest Paths (MCSP) where multiple options of shortest paths for routing in transparent optical networks result in different performance issues. In this section, the MCSP problem is extended to the case of translucent optical networks.

In translucent optical networks some paths are considered unfeasible routes due to optical physical layer impairments. Therefore, only shortest paths which are feasible routes will be taken into account hereafter.

Considering an optical network topology with *N* nodes, the total number of source-destination pairs is $N \times (N-1)$. We will use the notation *pair(s,d)* to represent an ordered pair of nodes, with its origin at node *s* and its destination at node *d*. For adaptive routing, it is necessary to set a dynamic route for each path request. If we assume that the *pair(s,d)* uses the same route as the *pair(d,s)* (bidirectional path), then it is sufficient to find forward routes only. Therefore, at least $R = (N \times (N-1))/2$ routes have to be computed for a determined topology with *N* nodes, in order to satisfy any path request *(s,d)*.

Most of the related works (Section II) use classical shortest path algorithms (e.g., Dijkstra's and Bellman–Ford's) to compute routes or to compose a routing solution, fixed, alternate or exhaustive. These classical algorithms, which usually are implemented as "modules" in others algorithms, aim at finding one shortest path for each *pair(s,d)*. However, between any two nodes (source and destination) it may be found more than one shortest paths. To illustrate this, consider a simple example of a translucent optical network based on the topology shown in Figure 2, here named as **R**ing with **6** **N**odes and one **T**ransversal **L**ink (R6NTL), where node 2 is a regenerator node. For instance, we observe that there are two shortest feasible paths between nodes 1 and 4 in R6NTL, either with three hops: 1–2–3–4 and 1–2–5–4. Therefore, without any other additional criterion, a classical shortest path algorithm applied to R6NTL may choose any of these three-hop paths for routing between nodes 1 and 4.

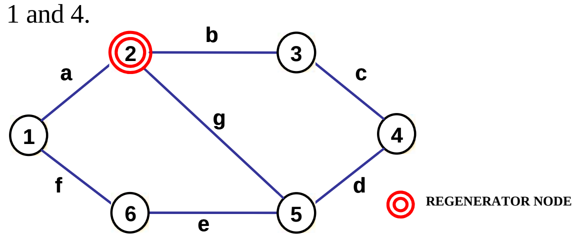

Figure 2. R6NTL Topology.

Now, generalizing to any translucent optical network topology, as for each *pair(s,d)* there may be more than one shortest path feasible route (called in this work Feasible Candidate Routes – FCR), there are *M* different solutions for selecting the feasible routes in a given network topology. The number *M* of possible solutions is given by

$$M = \prod_{i=1,\, j=1}^{N,N} FCR_{pair(i,j)} \qquad (1)$$

where $FCR_{pair(i,j)}$ represents the number of shortest path feasible candidate routes for the *pair(i, j)*, with $i \neq j$. Note that all candidate feasible routes have the least number of hops.

For the R6NTL topology, we have $M = 1^9 \cdot 2^6 = 64$ because this topology has nine pairs of source–destination nodes with only one feasible candidate route and six pairs with two shortest path feasible candidates. So, considering all shortest path feasible candidate routes for each *pair(s,d)* in the R6NTL topology, there are M = 64 different combinations of feasible shortest paths.

Table 1 shows all shortest path feasible candidate routes for each *pair(s,d)* in the R6NTL topology. For later comparison purpose, the routes computed by the PIARA algorithm [8] are indicated by an asterisk in Table 1.

TABLE I. FEASIBLE SHORTEST PATHS FOR R6NTL TOPOLOGY.

Pair (*s,d*)	Feasible Shortest Path	Pair (s,d)	Feasible Shortest Path
(1,2)	1-2*	(2,6)	2-1-6* 2-5-6
(1,3)	1-2-3*	(3,4)	3-4*
(1,4)	1-2-3-4* 1-2-5-4	(3,5)	3-2-5* 3-4-5
(1,5)	1-2-5*	(3,6)	3-2-1-6* 3-2-5-6
(1,6)	1-6-5*	(4,5)	4-5*
(2,3)	2-3*	(4,6)	4-5-6*
(2,4)	2-3-4* 2-5-4	(5,6)	5-6*
(2,5)	2-5*		

We can then define the problem of choosing the best combination among *M* Combinations of Feasible Shortest Paths (MCFSP) as how to identify a solution of feasible shortest paths routes S_k with $1 \leq k \leq M$, such that S_k provides the best network blocking probability performance. This new definition generalizes for translucent optical networks the previous definition of the MCSP problem [6].

To illustrate the MCFSP problem we can consider, besides R6NTL, the Germany and the European Optical Network (EON) topologies shown in Figure 3, two interesting topologies for translucent optical network studies [8,12], all having regenerator nodes placed randomly in such a way that there are no two adjacent nodes with regeneration capability. Table 2 presents the number of routes R of a solution S_k, the sum of the number of feasible candidate routes (ΣFCR) for all *pairs(s,d)* and the number *M* of solutions of the MCFSP problem considering different scenarios in terms of topology, regenerator placement and optical reach (i.e., Impairment Threshold).

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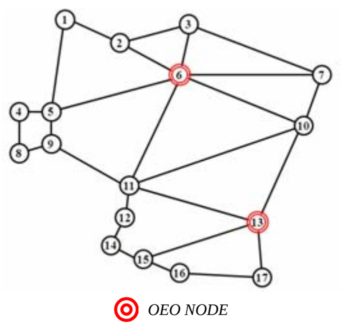
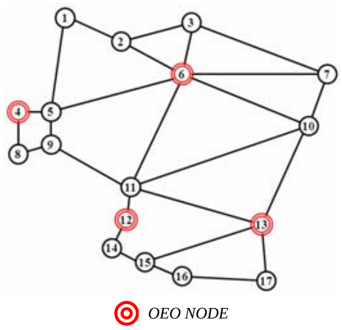
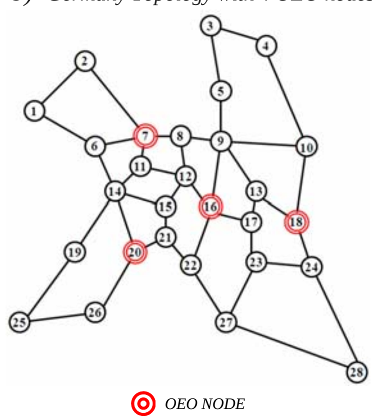


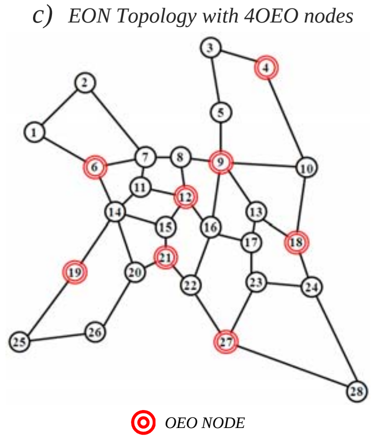
a) Germany Topology with 2 OEO nodes



b) Germany Topology with 4 OEO nodes



c) EON Topology with 4OEO nodes



d) EON Topology with 8 OEO nodes

Figure 3. Examples of translucent optical network topologies [12].

TABLE II. EXAMPLES OF THE MCFSP PROBLEM.

Network Topology	R	OEO Nodes	Optical Reach (*IT*)	ΣFCR	*M*
R6NTL (Fig. 2)	15	1	2 Hops	21	64
Germany Topology (Fig. 3)	136	2	2 Hops	368	$5{,}19\text{x}10^{33}$
			3 Hops	472	$1{,}35\text{x}10^{48}$
			5 Hops	526	$3{,}76\text{x}10^{57}$
		4	2 Hops	398	$3{,}02\text{x}10^{35}$
			3 Hops	480	$2{,}16\text{x}10^{49}$
			5 Hops	526	$3{,}76\text{x}10^{57}$
EON Topology (Fig. 3)	378	4	2 Hops	432	$3{,}02\text{x}10^{23}$
			3 Hops	1074	$1{,}92\text{x}10^{100}$
			5 Hops	1588	$7{,}43\text{x}10^{68}$
		8	2 Hops	765	$1{,}18\text{x}10^{169}$
			3 Hops	1620	$6{,}20\text{x}10^{71}$
			5 Hops	1800	$1{,}04\text{x}10^{189}$

In Table 2, we observe that the value of *M* increases very fast with the number of node pairs (*R*) and the number of feasible candidate routes for a specific *pair(s,d)*. Furthermore, we observe that the decrease of the optical reach (IT) reduces the number of feasible candidate routes too. However, even under low IT values (e.g., 2), the number of feasible shortest path combinations remains very high. This appears to be a good opportunity to apply new criteria to select feasible shortest paths in an adaptive routing scenario.

Algorithms using modules based on classical shortest path algorithm can find any solution S_k from the *M* solution set of the MCFSP problem. This happens because they do not consider any additional criterion in order to identify the best among the *M* possible solution combinations.

In order to show the variability of the network performance in terms of blocking probability when choosing from *M* combinations of shortest paths, we simulated all the *M* = 64 possible combinations of feasible shortest paths for R6NTL. In this case, it was found the best combination of feasible shortest path routes because of the simplicity of this topology, characterized by a few nodes and links. However, simulating all feasible shortest path combinations becomes impracticable with larger topologies (Figure 3 and Table 2).

Figure 4 shows a graph with 64 blocking probability curves for a hypothetical translucent optical network with the topology R6NTL (IT=2) as shown in Figure 2. The characteristics of this simulation study (number of lightpath requests generated, traffic type, wavelength assignment algorithm, etc.) are the same described later in Section V.

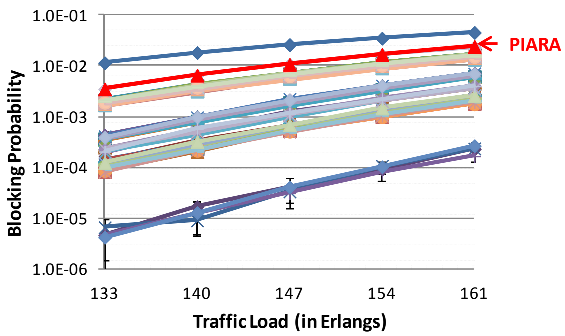


Figure 4. Blocking probability of all feasible shortest route combinations (M=64) of the R6NTL/IT=2 scenario.

Each curve in Figure 4 represents the performance in terms of blocking probability of one routing solution among the M = 64 possible solutions of the MCFSP problem as a function of the traffic load. The routing solution found by the PIARA algorithm [8] (Table 1) is highlighted for comparison purposes. Notice that PIARA, even being an exhaustive routing algorithm, will always find the same routes, as long as the optical reach (i.e., IT) remains the same. On the other side, these results (Figure 4) clearly show the large variability of performance among the several possible routing solutions, justifying a judicious planning strategy for choosing the set of feasible shortest routes in a translucent optical network.

Note that the number of combinations M in Table 2 is computed using Equation 1. A modified Dijkstra's algorithm is used only to compute the shortest path feasible routes (FCR) for each pair. The performance evaluation using all feasible route combinations in a small network (R6NTL) intends to exemplify the diversity of solutions of the MCSP problem, not to solve it. Actually, in larger networks, the routing strategy must avoid the need of scanning all feasible route combinations.

IV. PROPOSED HEURISTIC

This section presents a new algorithm for translucent optical networks named Best Shortest Translucent Lightpath (BSTL), which is an optical physical layer impairment-aware and adaptive routing algorithm. BSTL uses the link utilization measure (number of used wavelengths) to find the best solution for the MCFSP problem. The goal of BSTL is to balance the load among all links while reducing the blocking probability of lightpath requests, without breaking the optical physical layer constraints.

The execution of BSTL, as for any adaptive routing algorithm, is divided into two steps: alternate route computation and operation. The alternate route computation step occurs in the network planning phase. At the first step, all shortest routes for each *pair*(*s*,*d*) are previously computed by a modified Dijkstra's algorithm and stored for later checking and selection. For instance, for the R6NTL, the pre-computed BSTL routes are shown in Table 1. The second step of BSTL execution coincides with the operational phase where BSTL chooses, among the pre-computed set of feasible shortest paths, the feasible route with more availability of free continuous wavelengths to satisfy a specific source-destination lightpath request. This dynamic routing characteristic of BSTL is inspired in the Least Loaded Routing (LLR) algorithm [13]. LLR tries to satisfy a lightpath request using always the first of an ordered set of pre-computed alternative routes. Only if the first pre-computed route has no available resources, LLR will sequentially search a route among the other pre-computed alternative routes. However, as opposed to LLR, BSTL has a compromise with load balancing (frequency of use of wavelengths) among all pre-computed alternative routes.

A summary of the BSTL steps is as follows:

1) [Planning Phase] – Compute all shortest routes for each *pair(s,d)* by a modified Dijkstra's algorithm;
2) [Operational Phase] – Returns the feasible route, among the pre-computed ones, which has more available free continuous wavelengths.

The main idea of the BSTL is, at first, to compute off-line all feasible routes for each *pair(s,d)*, which is different from computing and simulating all M combinations of route solutions for a given topology and, secondly, to use the continuous wavelength availability criterion to dynamically select routes among the feasible routes pre-computed in a *pair(s,d)* basis. The load balancing strategy adopted by BSTL acts in order to prevent link bottlenecks which trends to compromise the network overall performance.

V. PERFORMANCE EVALUATION

The performance of BSTL was evaluated at different scenarios and compared to PIARA [8]. The different topologies and regenerator placements (randomly distributed, avoiding neighbor nodes) studied were those shown in Figures 2 and 3. The main metrics considered were network utilization and blocking probability. An additional metric corresponding to the fairness in satisfying the lightpath requests was also evaluated. The simulation tool TONetS [14] was extended to support the new characteristics of the translucent network routing algorithms here studied.

This simulation study, as well as the simulation results previously presented (Section III), has the following basic characteristics, usually assumed in similar studies about circuit-switched optical networks. Traffic demand is characterized by optical circuit (i.e., lightpath) requests in a *pair(s,d)* basis, uniformly distributed among all $N \times (N-1)$ pairs. Requests are generated based on a Poisson process with average rate λ and the lightpaths' hold times are exponentially distributed with mean $1/\mu$. The network's traffic intensity in Erlangs is given by $\rho = \lambda/\mu$. All network's links are bidirectional, having 40 wavelengths for each direction. *First-Fit* [4], by simplicity and good performance reasons, is used as the wavelength assignment algorithm. For each simulation, five replications are performed and five millions requests are generated for each replication. All graphical results express confidence intervals evaluated at the 95% confidence level.

A preliminary comparison between BSTL and PIARA, considering the R6NTL topology (Figure 2), is presented in Figure 5. The average utilization per link using BSTL or PIARA (under 161 Erlangs) is shown in Figure 5a. With PIARA, links ‘‘a” and ‘‘b” appear to be *overloaded* with an average utilization of 77%, approximately, while links ‘‘d” and ‘‘e” may be considered *underloaded* with an average utilization equal to 26%, approximately. On the other side, with BSTL, the average utilization of every link remains between 38% and 56% (Figure 5a), showing its effectiveness in terms of load balancing among the network’s links. Figure 5b shows the performance of BSTL and PIARA in terms of blocking probabilities. Observe that with BSTL, the route chosen for a specific lightpath request for the *pair(s,d)* cannot be the same route that satisfied the last request for the same pair. For instance, the BSTL solutions as shown in Figure 5b achieved a blocking probability performance of 0.0005, approximately, at the last load point (161 Erlangs), while PIARA achieved 0.024 under the same load.

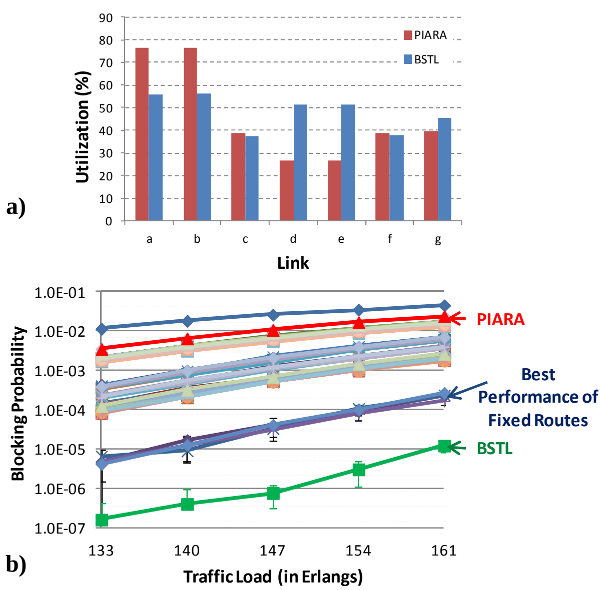


Figure 5. Link Utilizations (a) and Blocking Probabilities (b) for BSTL and PIARA algorithms in the scenario R6NTL/IT=2.

The average run time of PIARA in this preliminary study, considering the R6NTL/IT=2 scenario, was 1.1 millisecond, while BSTL took 0.04 millisecond for the same scenario. Notice that PIARA does not compute any route previously. On the contrary, PIARA computes routes dynamically under requests and considering the present state of the network. Therefore, as PIARA can select among any possible route, it would be expected its superior performance when compared to an alternate algorithm like BSTL which select routes from a pre-computed list. However, PIARA has a more complex implementation than BSTL, justifying its inferior run time behavior. With PIARA, it is necessary to gather link state information from all network links to compute partial routes and to generate the auxiliary graph that will conduct the selection of the final route. The BSTL strategy has an implementation less complex in the operational phase, because only links that compose the set of feasible candidate routes (pre-computed) are analyzed in the route selection procedure.

BSTL is also compared to PIARA considering the different topologies and OEO node placements shown in Figure 3. Firstly, the comparison is carried out in terms of blocking probabilities and network utilizations (Subsection A). Afterwards, fairness for each *pair(s,d)* is evaluated (Subsection B).

A. Blocking probabilities and network utilizations

The performance evaluation results with BSTL and PIARA in terms of blocking probabilities and network utilizations (i.e., average of the utilization of each network link) are presented in Figures 6.a to 6.d, considering the topologies of Figures 3a to 3d, respectively. The results achieved show a superior performance of BSTL for all evaluated scenarios. The better performance of BSTL can be explained because the routes chosen for each *pair*(*s*,*d*) are one of a *M* shortest path combination, and additionally, they are chosen aiming at link load balancing. On the other side, PIARA does not employ any additional criterion to choose a route besides the shortest path one.

From the network utilization point of view (Figure 6), BSTL's performance also appears to be superior because its lower blocking of lightpath requests; it also makes clear the advantages of its load balancing strategy. PIARA, which does not have a load balancing issue, becomes vulnerable to some “bottleneck links”, resulting in higher blocking probabilities and lower network utilizations than with BSTL.

B. Fairness

The metric of (average) blocking probability shows a general view of the success probability of satisfying a lightpath request in a specific topology scenario. Despite its usefulness, an average blocking probability metric tends to conceal the variability of blocking probabilities experimented by each *pair(s,d)*. In order to evaluate the impact of blocking probabilities in a *pair(s,d)* basis we define the fairness in satisfying a lightpath request as follows [15]:

$$Fairness = \frac{1 - Max\left(B_{p(s,d)}\right)}{1 - Min\left(B_{p(s,d)}\right)} \qquad (2)$$

where Bp(s,d) is the blocking probability for the pair(s,d).

This formula computes the ratio between the average blocking probability of the *pair(s,d)* with the worst performance and the blocking probability of the *pair(s,d)* with the best performance. The graphs presented in Figure 7 show BSTL's and PIARA's performances in terms of fairness for the topologies in Figure 3. It can be observed from these graphs that BSTL achieves better performances than PIARA for all evaluated scenarios. These superior performance results can also be explained by BSTL's load balancing strategy.

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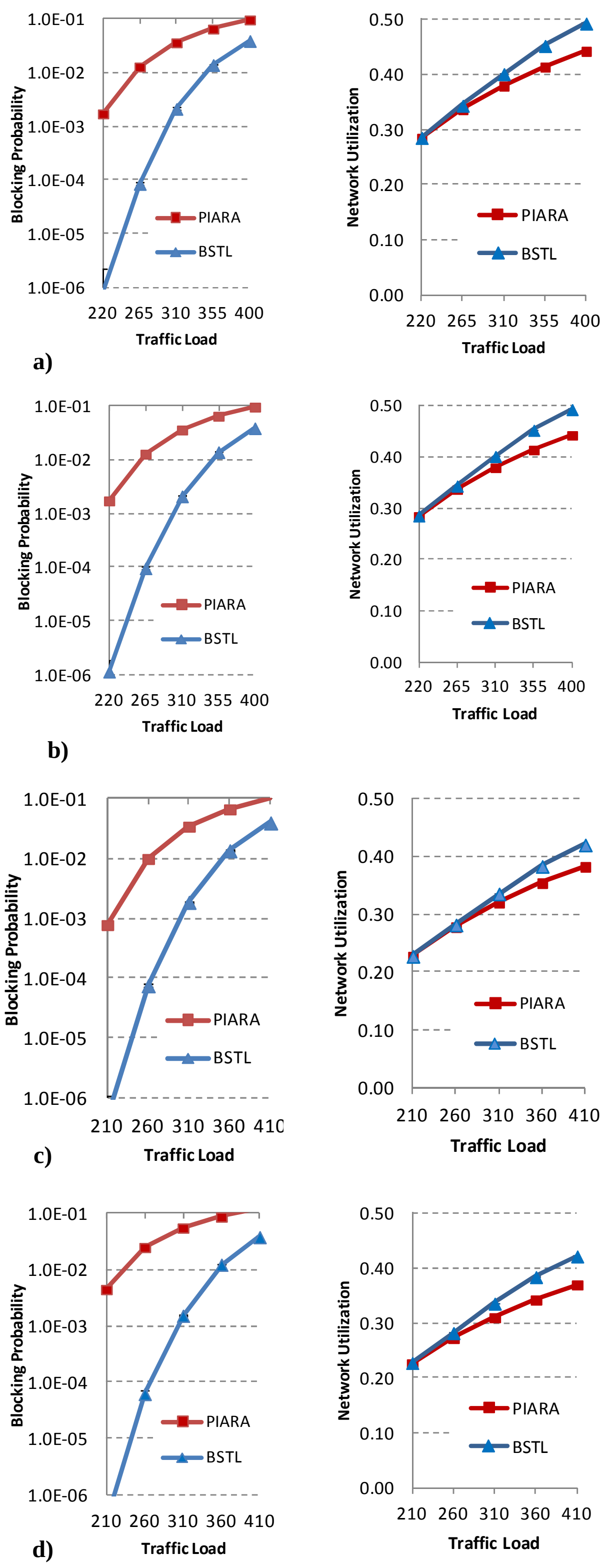

Figure 6. BSTL's and PIARA's blocking probability and network utilization performances.

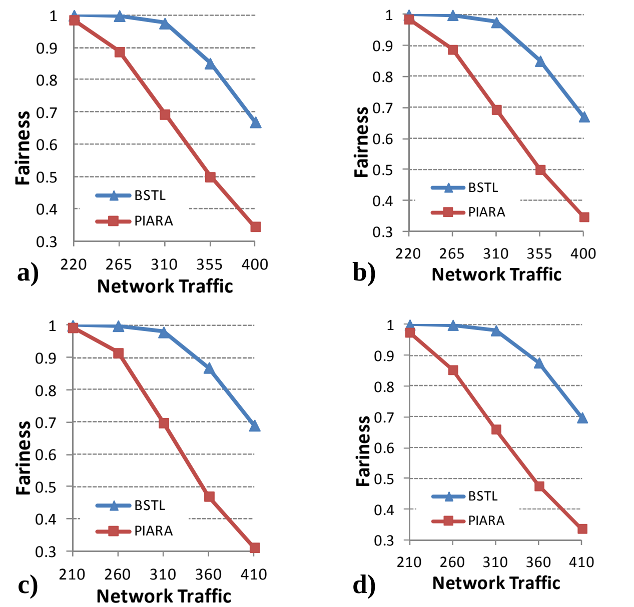

Figure 7. BSTL's and PIARA's fairness performances.

We also carried out performance studies of BSTL and PIARA with others topologies as the ones presented in [8] and [12]. In all the cases studied, BSTL achieved better performances.

VI. Final Remarks

This work presented a reformulation of the problem of the best choice of the shortest paths for translucent optical networks and proposed a new adaptive routing algorithm, named Best Shortest Translucent Lightpath (BSTL), that simultaneously considers optical physical layer constraints, shortest paths, and dynamic load balancing objectives. This new routing strategy had its performance evaluated and compared to another algorithm previously proposed in the literature, showing its superior performance in terms of network utilization, blocking probability and fairness when applied to translucent optical networks.

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