Classification Strategy to Mitigate Unfairness in All-Optical Networks

André Soares¹, William Giozza², Paulo Cunha³

¹,²Salvador University – UNIFACS, Salvador – Bahia, Brazil
³Federal University of Pernambuco – UFPE, Recife – Pernambuco, Brazil
andre.soares@unifacs.br, giozza@unifacs.br
prfc@cin.ufpe.br

Abstract—This paper investigates the fairness problem in all-optical networks without wavelength conversion under dynamic traffic loads. We propose a new classification strategy to mitigate the fairness problem called Fair-Fit. Our strategy is based on previous simulation studies that are carried out off-line. In addition, we introduce an equation that allows one to compare the source-destination pairs with the best and the worst blocking probability. Our simulation results show that Fair-Fit may result in better fairness results than earlier strategies proposed in the literature.

I. INTRODUCTION

Wavelength Division Multiplexing (WDM) is a technique which significantly improves the use of optical fiber bandwidth. Through application of this technique, several optical channels can be established at the same time, operating at different wavelengths within a single optical fiber [1]. In a wavelength-routed WDM network, end users are able to communicate with one another via all-optical WDM channels (lightpaths). In those optical networks, data are routed from the source node to the destination node through one or more wavelengths associated with a single lightpath. Each lightpath can easily support transmission rates of up to tens of Gbps with available commercial technology.

In circuit-switched optical networks [1], once a lightpath is established, it uses the full bandwidth of each wavelength assigned to it until the connection is terminated. When a connection is finished, all wavelengths that had been used become available again and can be used for future connections. To establish a lightpath, it is necessary to choose a route and to assign a wavelength (or wavelengths) at the different links forming the specified route. This problem is known as Routing and Wavelength Assignment (RWA) [2]. In an optical network with a dynamic traffic load, connections arrive upon demand. Therefore, route and wavelength choices need to be made quickly on-line. For optimization of the resource utilization of an all-optical network, routing and wavelength assignment have to be planned with the goal of minimizing the connection blocking probability. Without wavelength conversion capability at intermediary nodes, a lightpath must occupy the same wavelength on all the links of the established route. This property is known as the wavelength continuity constraint.

Wavelength converters are devices that can convert an input wavelength into a different output wavelength. A network with full wavelength conversion capability works as a common circuit-switched telephony network. Nevertheless, the relatively high cost and immaturity of wavelength converter technology still limits its use in all-optical network infrastructures [3].

Most studies evaluating the performance of RWA algorithms have focused specifically on the average blocking probability. This parameter indicates the average blocking probability for a request that is generated randomly (Bp). For a given network with N nodes there are \( N \times (N - 1) \) source-destination pairs. The blocking probability of a pair with source node \( s \) and destination node \( d \) \( (Bp_{(s-d)}) \) depends on the route chosen, the hop count and the utilization level of the links of the route. This means that different pairs (s-d) in the same network topology may have very distinct blocking probability values. Such characteristics should be considered as a form of unfairness in service. In [4] the authors show that it is expected that requests with longer routes (e.g. 4 or 5 hops) suffer higher blocking probabilities than requests with shorter routes (e.g. 1 or 2 hops). The length of the lightpaths (hop count) may vary with the network topology; that is, some s-d pairs use longer, and others shorter, routes.

To observe this unfairness characteristic, simulation experiments were carried out using the NSFnet network topology (Figure 1).

Fig. 1. NSFnet (16 nodes).

The blocking probabilities for all 240 s-d pairs under 550 Erlangs were found, as shown in Figure 2, using RWA based on the combination of the First-Fit wavelength assignment algorithm and the fixed routing strategy computed by shortest
The First-Fit algorithm and fixed routing computed by shortest path. Note that some pairs present practically no blocking. On the other hand, other pairs present blocking probabilities close to 60%. Clearly the network does not achieve the same blocking probability for all s-d pairs. This problem is called the Fairness Problem [5]. One way to solve such problems, or at least minimize the unfairness, should be to equalize the blocking probability between the s-d pairs.

One should notice that the analysis of the $Bp$ itself (average blocking probability of all s-d pairs) is not enough to gauge the level of the client’s satisfaction individually. Thus, for fairness purposes, it is important to know the quality of the service offered for each s-d pair in terms of its individual blocking probability, measured by $Bp(s-d)$.

In this work we propose a new methodology to classify connection requests so as to mitigate the Fairness Problem. The rest of this paper is organized as follows: related works and our contribution are presented in Section II. The proposed service classification strategy, named Fair-Fit, is presented in Section III. Section IV shows a performance evaluation study comparing the Fair-Fit classification strategy to others. Finally, Section V presents some conclusions.

II. RELATED WORK AND OUR CONTRIBUTIONS

Extensive research has been carried out in the field of RWA algorithms. Most of these studies proposed and evaluated RWA algorithms using the average blocking probability for a given request generated randomly ($Bp$).

A small number of works [5-7] have treated the Fairness Problem associated with RWA algorithms. In [5] the authors address this subject and propose the Traffic Classification and Service (ClasServ) Method to try to mitigate it. Pramod and Mouftah in [6] use a wavelength reserve to try to minimize the fairness problem and investigate the impact of different RWA algorithms on the wavelength reserve. Mosharaf, in [7], investigates the problem of optimal wavelength allocation and fairness control in all-optical rings.

In all of these previous works [5-7] the authors classify the lightpath requests according to the hop counts of the routes. That is, assuming a given network topology that has routes with 1, 2, 3 and 4 hops, the lightpath requests are classified by taking into account the hop count of the chosen route. This classification is used to allow the classes of lightpaths with high blocking probability - usually the requests with high hop counts - to have priority access to the resource.

Figure 3 illustrates an example of a traffic classification with different priority accessibilities mapped to wavelength subsets (wavebands) [5]. In this example (Fig. 3) the 40 wavelengths on each link are separated into 4 wavebands with 10 wavelengths each. Wavebands 1 and 2 can be accessed by every kind of class; waveband 3 can be accessed by 2-hop, 3-hop and 4-hop classes; and waveband 4 is reserved for 3-hop and 4-hop classes. A similar strategy is applied to NSFnet (16 nodes) with 240 wavelengths in order to mitigate the Fairness Problem.

![Fig. 2. Blocking probability for every s-d pair of NSFnet (16 nodes) using the First-Fit algorithm and fixed routing computed by shortest path.](image)

![Fig. 3. Classification and wavelength reservation based on the hop count strategy proposed in [5]](image)

After carrying out several simulation experiments with the NSFnet topology, we observed that classification of lightpath requests based on hop count may not be very useful in some cases. For instance, Figure 4 shows different $Bp(s-d)$ curves achieved for the pairs (3,11), (12,8), (8,4) and (4,10) picked out from the complete set of 240 s-d pairs. In particular, we noticed that pair (3,11) with 4 hops has achieved a lower blocking probability than pair (12,8) with 2 hops. Thus, although requests with longer routes usually suffer higher blocking probabilities than requests with shorter routes, this may not be true in all cases because the random nature of the traffic load is also a relevant factor.

Therefore, it may be interesting to consider this unexpected behaviour in the traffic classification process. Another weakness of classifications using the hop count metric is their lack of capacity to create subclasses that can differentially handle sets of lightpaths with equal hop counts. As far as we know, no work has ever been done applying a classification that takes into account a policy other than one using the hop count metric to mitigate the fairness problem of RWA algorithms. In this work we propose a new classification for lightpaths, called Fair-Fit, that considers the lightpaths performance in previous simulation studies. Our strategy, which can handle s-d pairs independently, aims to eliminate the ineffectiveness illustrated in Fig. 4.
III. FAIR-FIT CLASSIFICATION

The idea behind the Fair-Fit classification strategy is to identify which s-d pairs have higher $Bp(s-d)$ than a desirable peak threshold. After determining which s-d pairs have a low level of QoS (based on previous simulations), Fair-Fit will assign guaranteed priority access to such pairs by reserving some wavelengths to them. To better explain how Fair-Fit works, we apply it to the NSFnet topology (shown in Fig. 2) with 40 wavelengths, using a RWA based on First-Fit assignment and fixed routing calculated by the shortest path. The traffic is uniformly distributed across all s-d pairs.

The first step in Fair-Fit (iteration 1) is to simulate the network, measuring the $Bp(s-d)$ without classification: all s-d pairs initially belong to a single Class 0. Figure 5 shows the $Bp(s-d)$ for each pair of the set of 240 possible s-d connection pairs in the NSFnet network topology. This figure is very helpful for visualizing the QoS of each s-d pair ($Bp(s-d)$). The network utilization measure for the same scenario is shown in Figure 6.

Initially, one should notice that there is little fairness problem under low traffic load scenarios. This happens because there are many available wavelengths for a network under low utilization. Consequently, the blocking probability for any s-d pair is nearly zero. Thus, Fair-Fit is not carried out when the network has low utilization (i.e. in such traffic load conditions the Fair-Fit classification strategy is not useful). With the aim of measuring the difference in performance between the s-d pairs with the best and the worst blocking probability QoS, we propose the use a fairness measure based on the following equation:

$$Fr = \frac{1 - Max(Bp(s-d))}{1 - Min(Bp(s-d))}$$

Thus, our fairness measure is the ratio between the performance of the s-d pair with the worst QoS and the s-d pair with the best QoS. This fairness measure is used to evaluate the performance of different strategies proposed to mitigate the fairness problem. The fairness level increases when Fr values approach 1.

Considering that there is no fairness problem under low network utilization, it is important to define a threshold in terms of network utilization in order to apply the Fair-Fit classification in a useful way. The Fair-Fit classification is used only for network utilization values equal to or higher than this threshold. In this work we set the threshold to 45% network utilization, which is equivalent to a fairness level (Fr) of 0.8 for all of the scenarios studied.

The second step to carry out the Fair-Fit classification is to define a metric related to blocking probability in order to identify which of the s-d pairs need to have their QoS improved. Based on the results shown in Fig. 5 we assume a "peak target" blocking probability equals 0.35 for the 550 Erlangs (traffic load with the lowest fairness level). This peak target of blocking probability represents approximately 60% of the blocking probability peak achieved without classification. Therefore, the s-d pairs that achieve a $Bp(s-d)$ higher than 0.35 should have their QoS improved.

In order to improve the QoS of the s-d pairs identified in the previous step, we propose, as a third step, an iterative procedure to upgrade, by one unit, the class of those s-d pairs. To mitigate the fairness problem, Wi wavelengths are reserved for the s-d pairs of Class i. The value of Wi is proportional to the number of s-d pairs belonging to Class i.
Iteratively, the results obtained in the third step are analyzed and all the s-d pairs that show a \( Bp_{i(s,d)} \) higher than 0.35 will have their class upgraded by one unit for the next iteration. Each class \( i \) will only have \( Wi \) wavelengths able to be assigned to it or higher s-d pairs.

This iterative procedure may either create a new class after each iteration or a change in the number of \( Wi \) for each class \( i \), and it will terminate when new iterations do not improve their Fr when compared to previous iterations. The final classification will be the one that achieves the best value for Fr. Figure 7 exemplifies this iterative process considering only 5 s-d pairs. In the first iteration, all s-d pairs have the same classification (Class 0). Pairs (4,9), (14,13) and (5,14), having achieved a \( Bp_{i(s,d)} \) higher than 0.35, will belong to Class 1 on the next iteration. In iteration 2, pairs (4,9) and (5,14) achieved a \( Bp_{i(s,d)} \) higher than 0.35 and will be classified as Class 2 in iteration 3.

Figure 8 shows the performance achieved without classification, using Fair-Fit, and with ClaServ. Figures 10 and 11 show the performance of \( Bp_{i(s,d)} \) achieved using Fair-Fit and ClaServ, respectively.

The results of our strategy, which aimed to decrease the difference in performance between the clients' connections with the best and the worst QoS, should be noted in Figure 11. One should also see that the curves of \( Bp_{i(s,d)} \) are less scattered in Figure 11 than in Figure 10. This means that a better classification is achieved by examination of the performance of each s-d pair individually. Moreover, the peak

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\]

Simulations were carried out on the NSFnet topology (Fig. 1). For each simulation, 10 replications with different seeds of a random variable were run, and for each replication, 100,000 connection requests were generated.

The simulation studies were carried out using TONetS [8], a simulation tool developed to study RWA algorithms, survivability techniques and wavelength converter placement in all-optical networks. Our simulation tool has been partially validated through comparison with results of the simulation and analytical models presented in [9,10].

Figure 9 shows the fairness level achieved without classification, using Fair-Fit, and with ClaServ. Figures 10 and 11 show the performance of \( Bp_{i(s,d)} \) achieved using Fair-Fit and ClaServ, respectively.

One should note that compared to the same scenario without classification, the fairness level has been improved by applying the Fair-Fit strategy (Figure 8).

### IV. FAIR-FIT PERFORMANCE EVALUATION

In this section we present a performance evaluation study for the Fair-Fit classification strategy proposed. This study is based on discrete-event simulations. The performance of Fair-Fit is compared with the ClaServ method proposed in [5]. A dynamic traffic model is used in the simulations such that connection requests that arrive at the network follow a Poisson process with an average rate \( \lambda \). The load is distributed uniformly across all s-d pairs. The holding time of the connections is distributed exponentially with an average rate \( 1/\mu \). All links are bi-directional and each one has 40 wavelengths both ways. The network load is given by \( \rho = \lambda/\mu \); the wavelength assignment algorithm used is First-Fit. The routing, which is fixed, is calculated by the shortest path. The network does not have wavelength conversion capacity.

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Fairness levels achieved by Fair-Fit, ClaServ and a network without classification.

Both values are analyzed for a traffic load of 550 Erlangs.

Compared to ClaServ and the case without classification, Fair-Fit achieved the best performance (Fig. 9). As analyzed in Section III (Fig. 5), the fairness level is near 1 under a condition of low network utilization. The inferior Fr performance of ClaServ under low traffic loads may be justified, since it indiscriminately applies the same classification for all values of traffic load. That is, ClaServ uses the same classification model even when there is no fairness problem (under low traffic loads and, consequently, low network utilization).

Carrying out simulation studies using other network topologies like EON and Abilene, we noticed behaviours very similar to those found in the NSFnet network topology. These results were omitted due to lack of space.

V. CONCLUSION

This work investigated the fairness problem for all-optical networks without wavelength conversion under dynamic traffic load. We identified some unfairness characteristics that are usually neglected by studies based on Bp metrics only. We proposed a new strategy to classify and to reserve wavelengths with the goal of mitigating the fairness problem. This strategy, called Fair-Fit, involves definition of an equation for measuring the level of fairness and the traffic load condition whereupon fairness becomes a problem. A performance evaluation study was carried out showing that our strategy mitigated the fairness problem and achieved better performance than other classification methods.

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