Fairness in Two-Rate Elastic Optical Networks

Joobum Kim
Korea Institute of Science and Technology Information

Abstract

Routing and Spectrum Assignment (RSA) algorithms are key factor to increase the efficient spectrum utilization in Elastic Optical Networks (EON). Currently a variety of RSA algorithms have been proposed to increase spectrum efficiency, but they usually focus on the overall blocking probability as a main performance indicator. In this paper an additional performance indicator is introduced to quantify the level of fairness (or unfairness) experienced by two types of demands, each type requiring a distinct spectrum bandwidth. The authors propose new RSA algorithm to control blocking probability and the level of fairness by partitioning the spectrum into dedicated and shared bands. From the simulation results, the trade-off between the overall blocking probability (experienced by all demands) and the level of fairness achieved by RSA algorithms is quantified.

I. Introduction

Due to the explosive network traffic growth, efficient spectral resource management is becoming more important in Elastic Optical Networks (EONs). EONs make possible to achieve better spectrum utilization by allocating spectrum resources (slices) proportionally to the amount of traffic requested by demands compared to the traditional WDM networks [1], [2]. However, accomplishing better efficient spectral resource utilization can be disturbed by the fragmentation of spectrum slices. Fragmentation refers to the occurrence of non-continuous small spectrum slices that can not be utilized for accommodating a large size of slices requested by demands. The fragmentation effect is more deteriorated by combining with the spectrum continuous constraint in computed paths across the network.

The studies in [1]–[9] have been conducted to alleviate the fragmentation effect recently. In these research, several RSA (Resource and Spectrum Allocation) algorithms are introduced and their performance is shown to estimate the spectrum utilization across network. As a performance indicator, overall blocking probability is used in these studies. These are some of the RSA algorithms proposed so far. The work in [3] investigates the advantages of combining the K shortest paths (KSP) approach with the First-Fit spectrum slice allocation algorithm when dealing with the fragmentation problem, and analyzes the computation complexity of the proposed technique. In [4] the RSA problem is formulated as an integer linear programming problem and two algorithms — Greedy-Defragmentation and Shortest Path-Defragmentation — are proposed to confine the existing connections towards the lower side of the spectrum in order to mitigate the adverse effects of spectrum fragmentation. The study in [5] introduces the concept of cut and misalignment in order to quantify spectrum fragmentation in EON, and then proposes two RSA algorithms — Fragment-Aware and Alignment-Aware — to mitigate the fragmentation problem. The authors of [6] propose a dynamic routing and frequency semi-flex slice assignment algorithm that employs distance adaptive modulation to achieve lower blocking probability.

However, one aspect which is overlooked in these studies is the level of fairness achieved by RSA algorithms when allocating spectrum slices to requested demands. As a matter of fact, demands requesting a large continuous spectrum slices is more likely to experience higher blocking compared to those requesting a small continuous spectrum slices. The study of fairness has been investigated in [10]. Although the proposed algorithm in [10] offers the fairness, but typical performance metric such as blocking probability is not guaranteed.

In this paper, the authors investigate the fairness and overall blocking probability accomplished by several RSA algorithms in a two-rate EON. In a two-rate EON, there are only two distinct sizes of demands, i.e, one is group 1 and the other is group 2. This paper describes the proposed algorithm (TTR) which is designed to investigate the partitioning the spectrum. In detail, the spectrum in a link is partitioned by three subsets of slices, i.e, N_1, N_2 and N_s. N_1 and N_2 is dedicated for serving demands from group 1 and group 2, respectively, and N_s is shared by two groups.

The fairness performance indicator (F) is formally defined for a two-rate EON and then estimated for TTR and other well-known RSA algorithms, i.e., Trunk Reservation, First-Fit, Fragment-Aware, Alignment-Aware, semi-flex and fixed-multiplexing algorithms. In the study, simulation experiments conducted on the NSF topology under a variety of offered traffic loads. Such results are shown to clearly illustrate the trade-off between the overall blocking probability and the level of fairness achieved by each RSA algorithm. Furthermore the proposed algorithm shows the better fairness and blocking probability compared to other RSA algorithms for some experiment cases. The results also reveal an unexpected oscillating behavior of the fairness level as a function of the offered load, which is corroborated by a numerical analysis obtained using the analytical framework in [11].

II. Blocking and Fairness in Two-Rate EON

A two-rate EON [12] supports only two groups of connection demands, i.e., group 1 and group 2. The EON fibers' spectrum is divided to form a total of N contiguous slices, which are progressively numbered from 0 to $N-1$. A demand in group 1 requires $m = 1$ contiguous slices of the optical spectrum. A demand in group 2 requires $n \times m = n$ contiguous slices of the optical spectrum, where n is an integer value[1]. A demand that cannot be placed in the network due to insufficient availability of slices along the fiber links of the path(s) connecting the source to the destination of such demand is blocked. Let BP denote the overall blocking probability experienced by demands in both groups. Let BP_1 denote the blocking probability experienced by group 1 and BP_2 denote the blocking probability experienced by group 2, respectively. The Fairness (F)

$$F = \frac{BP_2}{BP_1} \tag{1}$$

is a performance indicator as to how fairly (or unfairly) the two-rate EON is handing demands across the two groups. Naturally, $F = 1$ represents a perfectly fair system as demands in both groups are experiencing the same level of blocking. A decreasing level of fairness is denoted by F values departing from 1 (above or below such value).

Let λ_1 represent the arrival rate of group 1 and λ_2 represent the arrival rate of group 2, respectively. The Arrival Rate Ratio (AR)

$$AR = \frac{\lambda_1}{\lambda_2} \tag{2}$$

is a indicator as to how many demands from group 1 or group 2 are coming into the system. Based on the value assigned to AR

- $AR = 1(\lambda_1 = \lambda_2)$: in this case the number of generated demands of group 1 and 2 is equal;
- $AR > 1(\lambda_1 > \lambda_2)$: in this case the number of demands from group 1 is larger than those from group 2;
- $AR < 1(\lambda_1 < \lambda_2)$: in this case the number of demands from group 2 is larger than those from group 1;

Seven RSA algorithms are going to be evaluated in terms of both performance indicators, i.e., BP and F. These two combined key performance indicators offer a more comprehensive evaluation of such algorithms' performance when compared to using only BP. The seven algorithms are briefly described in the next section.

A. Six Known RSA algorithms

This section provides a brief description of six known RSA algorithms, which are evaluated in terms of both blocking and fairness performance in Section III.

Trunk Reservation. Trunk reservation algorithm is designed to guarantee the fairness [10] . For a source-destination node pair in the network, the shortest path is computed. In order to accept a demand, trunk reservation algorithm imposes an additional constraint in which a continuous available slice of bandwidth on a route has to be larger than the maximum size of slice bandwidth requesting by demands of any type. In doing so, the algorithm enforced to meet the same congestion levels of demands of any type.

KSP. The k-shortest path heuristic algorithm combines the k-shortest path algorithm with the First-Fit [7] slice assignment [3]. For every source-destination node pair in the network, K shortest paths are computed and stored in memory. Hop-count is used as the metric to sort the best K paths, which need not be link nor node disjoint. A connection demand requiring y slices is assigned one of the K paths as follows. For each path, the first available group of y consecutive spectrum slices is computed, starting from one end of the spectrum (say, from slice number 0). If a path does not have at least one such group of slices, the path is excluded from the assignment process. All the other paths are then compared using their respective slice group assignment. The path with the lowest slice identifier is assigned to the connection demand, along with the chosen group of slices.

Fragmentation-Aware Algorithm. The fragmentation-aware RSA algorithm is designed to reduce the fragmentation of the fiber spectrum into disjoint groups of slices [8]. The algorithm takes into account the number of times a contiguous group (or block) of slices is partitioned into two disjoint groups by the "placement" of a connection demand that is assigned a subset of slices in such block. This occurrence is called a "cut." For each of the K shortest paths available, the algorithm finds the slice assignment that generates the minimum number of total cuts experienced across all of the fiber links in the path. The K paths are sorted by increasing number of cuts and the first path is assigned to the connection demand, along with the chosen group of slices. If two or more paths have the same number of cuts, the path offering the lowest slice identifier is chosen (First-Fit).

Alignment-Aware Algorithm. The alignment-aware algorithm is designed to reduce the misalignment of available slices between fiber pairs that are incident to a common node [8]. The misalignment cost is defined as the number of slices that are *not* commonly available in the two fibers. In other words, the more common slices are available in the two fibers, the lower is the misalignment cost measured. For each of the K shortest paths available, the algorithm finds the slice assignment that generates the minimum misalignment cost across all of the fiber links in the path. The K paths are sorted by increasing value of misalignment cost and the first path is assigned to the connection demand, along with the chosen group of slices. If two or more paths have the same misalignment cost, the path offering the lowest slice identifier is chosen (First-Fit).

[1] The generalization to any integer $m > 1$ is a straightforward exercise.

Semi-flex. This RSA algorithm is designed to operate in a *semi-flexible grid* EON, in which slice sensitive switching nodes (WSS) have limited switching capabilities [9]. In this solution the spectrum slices are grouped to form predefined equal-size blocks, and slices are assigned to connection demands according to such block allocations. For example, in the two-rate EON, the block size is n slices. Assuming that the N/n ratio is an integer value, the spectrum is then subdivided to form the following predefined blocks of slices: $(0, n-1)$, $(n, 2n-1)$, $(2n, 3n-1)$, $(N-n, N-1)$. When assigning slices to a demand of group 2, only one of these predefined blocks can be assigned to such demand. When assigning a slice to a demand of group 1, any slice can be assigned, regardless of the predefined blocks. Subject to this semi-flex slice assignment constraint, the algorithm used to both compute the path and assign a group of slices to a connection demand is the same one described for the KSP algorithm.

Fixed. This algorithm is a trivial application of resource partitioning to the RSA problem. Each group of demands is reserved a dedicated portion (or band) of the spectrum. Each band is then subdivided into an integer number of predefined blocks of slices, each block size matching the number of slices required by the demands in that group. A demand of a given group can only be assigned one of the predefined blocks in its own band. Demands that belong to distinct groups are not allowed to share slice identifiers. The first advantage of this solution is to ensure that each group of demands is guaranteed a predefined amount of slices. By properly partitioning slices across the demand groups, it is possible to manually control the level of blocking for each group. The second advantage is to reduce the complexity of the fragmentation problem, which for the Fixed solution, can be easily shown to be equivalent to the traditional fragmentation problem of fix-grid networks. For the two-rate EON, for example, the N slices can be partitioned to form two bands as follows: $N_2 = n \times x$ slices are reserved to serve demands of group 2 and the remaining $N_1 = N - n \times x$ slices are reserved to serve demands of group 1, where x is an integer value that depends on the arrival rate (volume) of each demand group and the desired level of blocking and fairness. Assuming an equal arrival rate (or volume) for each demand group, a simple choice is $x = \lfloor N/(n+1) \rfloor$, which offers a good compromise between obtaining a low overall blocking (BP) and a good fairness level (F). The results in Section III refer to this particular band allocation.

B. Two Rate Reservation Algorithm (TRR)

The aforementioned advantages of the Fixed RSA algorithm are in part counterbalanced by its overall poor blocking probability (BP), as quantified in Section III. Indeed, the fixed partitioning of the spectrum does not allow slices to be statistical multiplexed by demands from both groups, which is the main reason for this poor performance.

Let the optical spectrum be divided into three disjoint bands (or sets) of contiguous slices, such that $N_1 + N_2 + N_s = N$, where N_1 is the number of slices reserved to group 1 demands, N_2 is the number of slices reserved to group 2 demands, and N_s is the number of slices that are shared by both groups. N_1 is chosen to be an integer multiple value of m and N_2 is chosen to be a integer multiple value of n. These spectrum bands are further subdivided to form predefined blocks of slices as already described for the Semi-flex algorithm. By controlling the two values (or thresholds) N_1 and N_2, one can achieve the desired trade-off between blocking and fairness performance.

In the Two Rate Reservation Algorithm (TRR), First-Fit is applied from the lowest slice identified to demands from both groups.

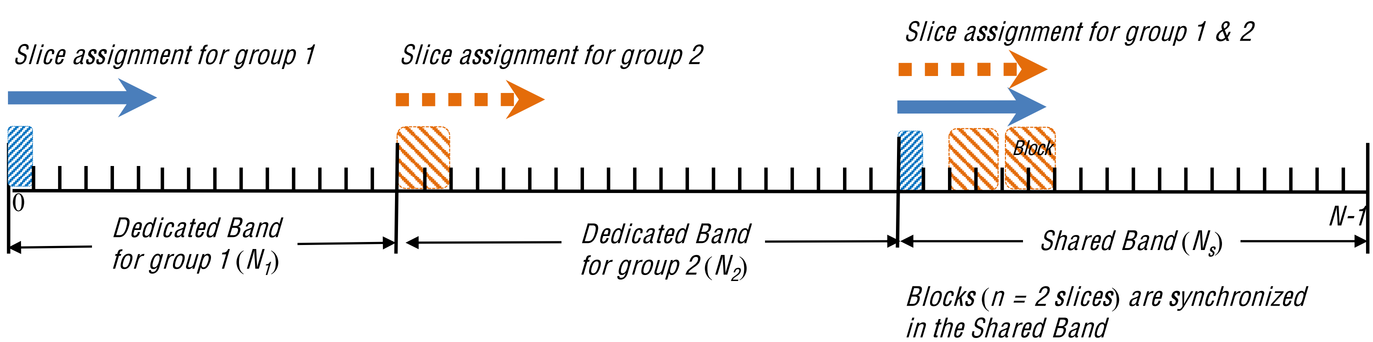

Fig. 1. TTR algorithm ($m = 1$ and $n = 2$).

Fig. 1 depicts the three-way spectrum partitioning and First-Fit sequence used by the TTR algorithm for the case of $m = 1$ and $n = 2$. The set of N_s shared slices is subdivided to form predefined blocks of $n = 2$ slices, starting from the lowest slice identifier. The procedure used to allocate the slice to a demand of group 1 is as follows. For each path in the recorded set of k shortest paths from the source to destination node of the connection demand the algorithm searches for the slice with the lowest possible identifier. Considering all the fiber links in the path, a commonly available slice is chosen by first searching in the dedicated set of N_1 slices. The slice with the lowest identifier in this set is assigned. If a slice cannot be found in the dedicated set (N_1), the algorithm goes on to search a slice in the set of N_s shared slices. The available slice with the lowest identifier in this set is then allocated. If a slice cannot be found in the shared set, the corresponding path is excluded from the computation. All the other paths are then compared using their respective slice identifiers. The path with the lowest slice identifier is assigned to the connection demand, along with the chosen slice.

A similar procedure is used to assign a pair of ($n = 2$) contiguous slices to each demand of group 2. The only difference is that only predefined blocks of slice pairs can be assigned to such demand in both reserved set of N_2 slices and shared set of N_s slices. Two allowed slice allocations are shown in Fig. 1 in orange.

III. Results and Analysis

This section describes the performance of RSA algorithms in Elastic Optical Network which is conducted by a discrete event driven simulator. In the simulator, Blocking Probability (BP) and Fairness (F) are used to estimate the performance.

In this experiment, the NSF topology with 14 nodes and 21 links is used and each link has two unidirectional fibers (one per direction). Each fiber spectrum is divided into $N = 400$ slices [5]. For each node pair in the topology, the number of shortest paths ($k = 5$) are computed using hop-count as the metric. The number of slices per request is varied in the set $(1, 2, 4, 8)$. Connection demands are generated according to a Poisson arrival process, whose rate is varied to achieve eight distinct offered loads that yield most of the results for BF in the $[10^{-5}, 1]$ range. Results are not shown when their values are too low for BP or too high for F. In some cases $F = \infty$. The assigned value of the arrival rate ratio (AR) is varied in the set $(0.2, 0.5, 1, 2, 5)$ when running an experiment. The source and destination nodes for each connection demand are uniformally and randomly chosen. The demand lifetime is a random variable with exponential distribution.

As is shown in Table I, depending on AR value, the offered traffic load (ρ) is changed to generate an overall blocking probability range in $[10^{-5} - 10^{0}]$. For example, in Case 2 ($m = 1, n = 2$ and $AR = 0.5$) the number of demands of group 2 requiring 2 slices is doubled than the number of those of group 1 requiring 1 slice. In Case 4 ($m = 1, n = 2$ and $AR = 2$) the number of demands of group 1 requiring 1 slice is doubled than the number of those of group 2 requiring 2 slices. The total requested amount of slices of Case 2 is higher than those of Case 4, because there exist more demands of group 2 in Case 2 than those of group 2 in Case 4. Therefore traffic loads should be decreased in Case 2 and increased in Case 4 to be equal.

TABLE I
EXPERIMENT PARAMETERS.

Case	m	n	AR	Case	m	n	AR	Case	m	n	AR
1	1	2	0.2	6	1	4	0.2	11	1	8	0.2
2	1	2	0.5	7	1	4	0.5	12	1	8	0.5
3	1	2	1	8	1	4	1	13	1	8	1
4	1	2	2	9	1	4	2	14	1	8	2
5	1	2	5	10	1	4	5	15	1	8	5

A. $m = 1$, $n = 2$, $AR = 1$

Fig. 2 shows the blocking probability versus fairness indicator for seven known RSA algorithms using $m = 1$, $n = 2$ and $AR = 1$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, TRR, Semi-flex, First-Fit and Frag-Aware. The Alignment-Aware algorithm is not shown as its F value is infinity. Fig. 3 further investigates the two performance indicators for the four best RSA algorithms in terms of achieved F values, along with the algorithm proposed in this paper, i.e., Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers a trade-off between Semi-flex and Trunk Reservation, the former offering the best blocking and the latter offering the best fairness indicator. In TRR, as the size of the shared band increases(decreases), the blocking probability decreases(increases), but the fairness indicator increases(decreases). TRR offers better fairness performance while maintaining a competitive blocking probability when compared to Semi-flex.

B. $m = 1$, $n = 2$, $AR = 2$

Fig. 4 shows the blocking probability versus fairness indicator for the seven RSA algorithms using $m = 1$, $n = 2$ and $AR = 2$. The Alignment-Aware algorithm is not shown as its F value is infinity. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, TRR, Semi-flex, First-Fit and Fragmentation-Aware. The Alignment-Aware algorithm is not shown as its F is infinity. Fig. 5 further investigates the two performance indicators for the four best RSA algorithms in terms of achieved F values, along with the algorithm proposed in this paper, i.e., Trunk Reservation, Fixed, Semi-flex and TRR. Semi-flex offers the best blocking probability and Trunk Reservation offers the best fairness performance. TRR algorithm offers better fairness performance while maintaining a competitive blocking probability when compared to

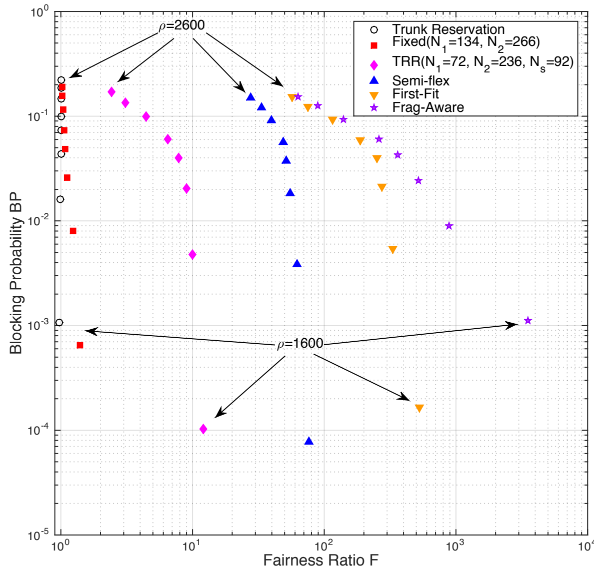

Fig. 2. Blocking probability (BP) versus fairness (F) for known RSA algorithms with $m = 1$, $n = 2$ and $AR = 1$. The range of traffic load (ρ) is 1600 to 2600.

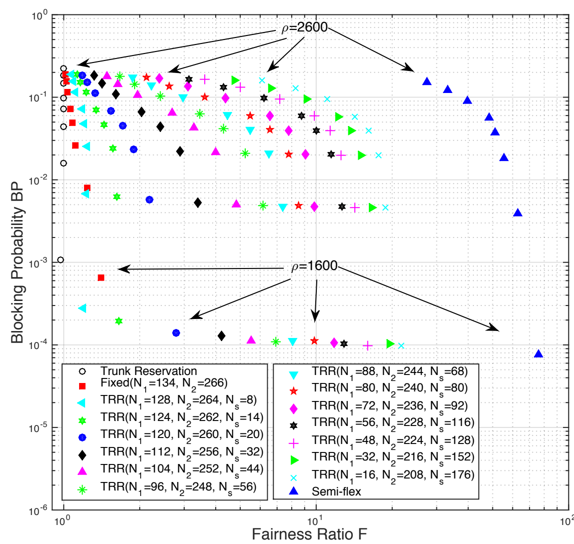

Fig. 3. Blocking probability (BP) versus fairness (F) for known RSA algorithms with $m = 1$, $n = 2$ and $AR = 1$. The range of traffic load (ρ) is from 1600 to 2600.

Semi-flex, because TRR allows a controlled amount of slices to be statistically multiplexed between from group 1 and group 2.

C. $m = 1$, $n = 2$, $AR = 0.5$

Fig. 6 shows the blocking probability versus fairness indicator for RSA algorithms using $m = 1$, $n = 2$ and $AR = 0.5$. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, TRR, Semi-flex, First-Fit and Frag-Aware. Fig. 7 further investigates the two performance indicators for the four best RSA algorithms in terms of achieved F values, along with the algorithm proposed in this paper, i.e., Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers improved fairness performance compared to Semi-flex by about one order of magnitude while maintaining a similar blocking probability compared to Semi-flex.

D. $m = 1$, $n = 2$, $AR = 5$

Fig. 8 shows the blocking probability versus fairness indicator for RSA algorithms using $m = 1$, $n = 2$ and $AR = 5$. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, TRR, Semi-flex, First-Fit and Frag-Aware.

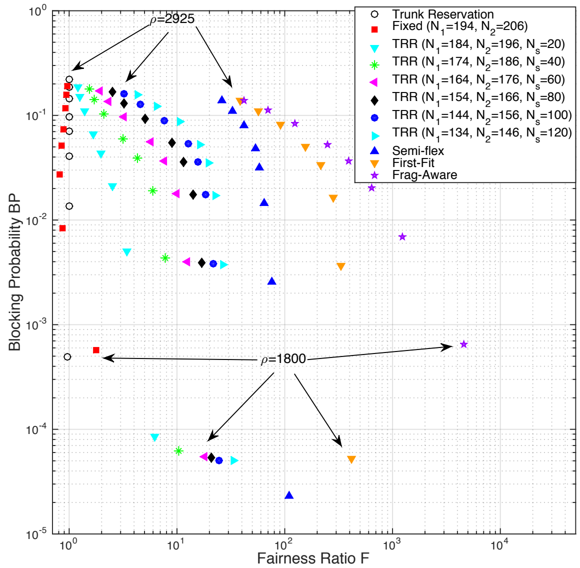

Fig. 4. Blocking probability (BP) versus fairness (F) for known RSA algorithms with $m = 1$, $n = 2$ and $AR = 2$. The range of traffic load (ρ) is from 1800 to 2925.

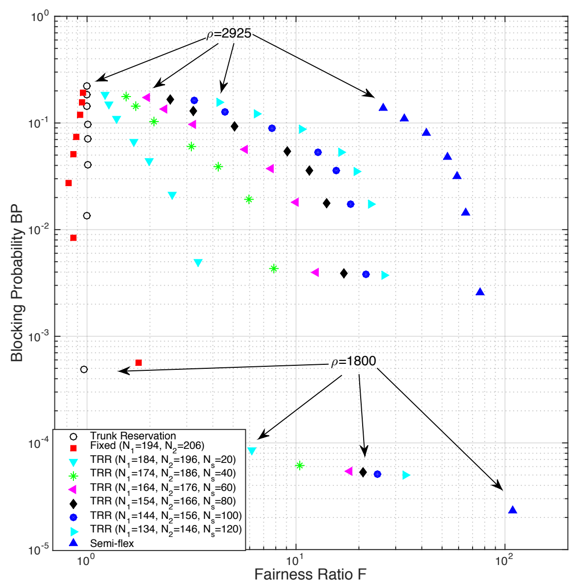

Fig. 5. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 2$ and $AR = 2$. The range of traffic load (ρ) is from 1800 to 2925.

Fig. 9 further investigates the two performance indicators for the four best RSA algorithms in terms of achieved F values, along with the algorithm proposed in this paper, i.e., Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers a better fairness indicator, but it shows slightly higher blocking probability compared to the Semi-flex.

E. $m = 1$, $n = 2$, $AR = 0.2$

Fig. 10 shows the blocking probability versus fairness indicator for RSA algorithms using $m = 1$, $n = 2$ and $AR = 0.2$. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, TRR, Semi-flex, First-Fit and Frag-Aware. Fig. 11 further investigates the two performance indicators for the four best RSA algorithms in terms of achieved F values, along with the algorithm proposed in this paper, i.e., Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers improved fairness indicator compared to Semi-flex by more than one order of magnitude while maintaining a similar blocking probability compared to Semi-flex.

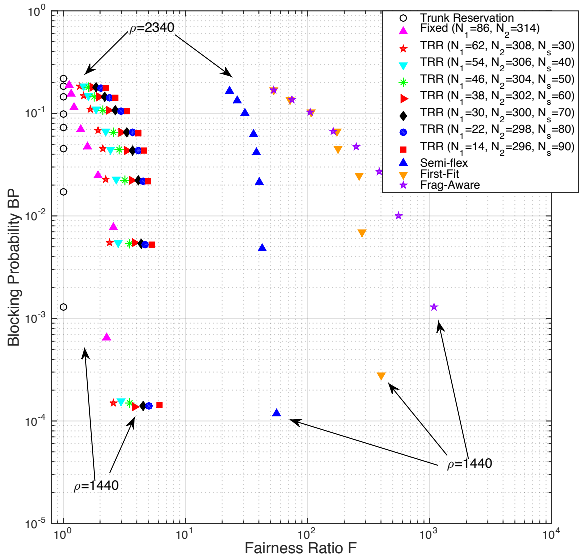

Fig. 6. Blocking probability (BP) versus fairness (F) for known RSA algorithms with $m = 1$, $n = 2$ and $AR = 0.5$. The range of traffic load (ρ) is from 1440 to 2340.

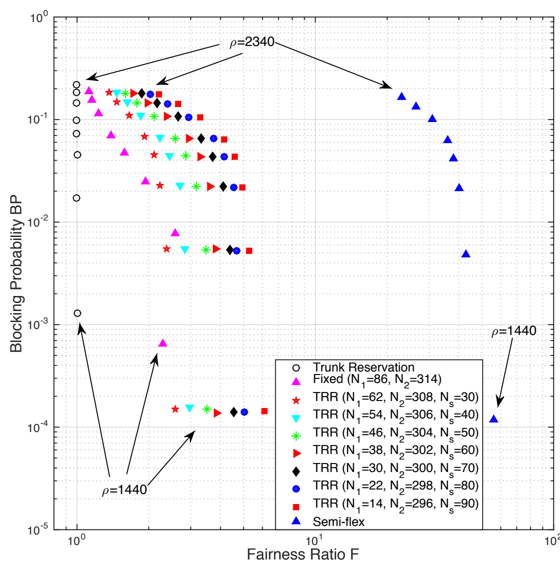

Fig. 7. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 2$ and $AR = 0.5$. The range of traffic load (ρ) is from 1440 to 2340.

F. $m = 1$, $n = 4$, $AR = 1$

Fig. 12 shows the blocking probability versus fairness indicator for four RSA algorithms using $m = 1$, $n = 4$ and $AR = 1$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers improved fairness performance compared to Semi-flex by about one order of magnitude while maintaining a competitive blocking probability when compared to Semi-flex, because TRR allows a controlled amount of slices to be statistically multiplexed between from group 1 and group 2.

G. $m = 1$, $n = 4$, $AR = 2$

Fig. 13 shows the blocking probability versus fairness indicator for four RSA algorithms using $m = 1$, $n = 4$ and $AR = 2$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers not only improved fairness performance compared to Semi-flex by about one order of magnitude, but also offers better blocking probability performance.

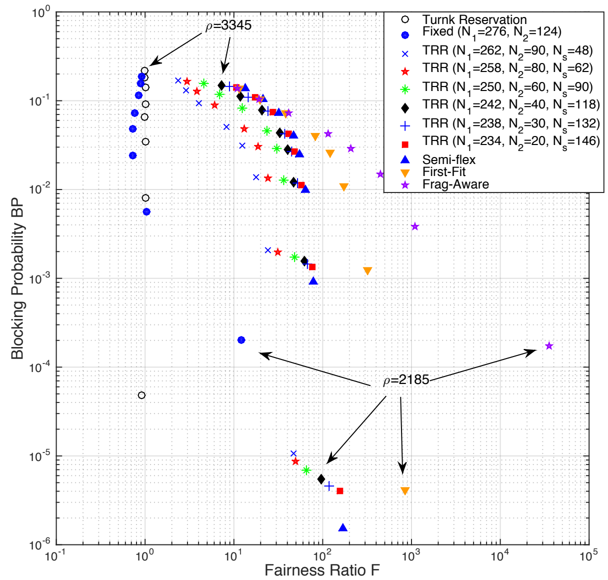

Fig. 8. Blocking probability (BP) versus fairness (F) for known RSA algorithms with $m = 1$, $n = 2$ and $AR = 5$. The range of traffic load (ρ) is from 2185 to 3345.

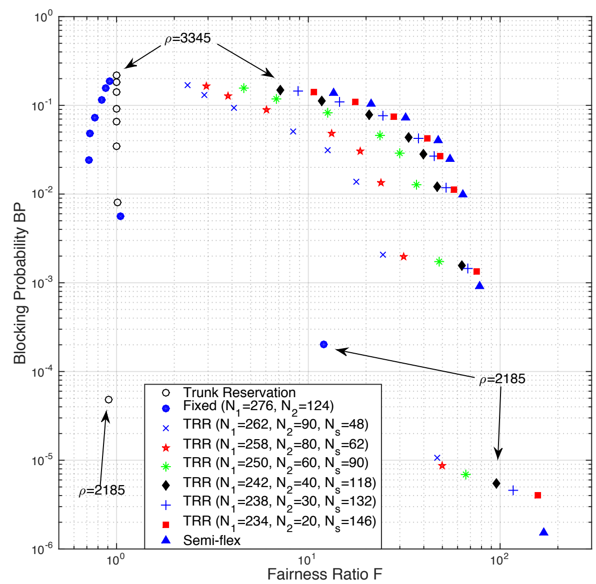

Fig. 9. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 2$ and $AR = 5$. The range of traffic load (ρ) is from 2185 to 3345.

H. $m = 1,\ n = 4,\ AR = 0.5$

Fig. 14 shows the blocking probability versus fairness indicator for four RSA algorithms using $m = 1$, $n = 4$ and $AR = 0.5$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers not only improved fairness performance compared to Semi-flex by more than one order of magnitude, but also offers better blocking probability performance.

I. $m = 1,\ n = 4,\ AR = 5$

Fig. 15 shows the blocking probability versus fairness indicator for four RSA algorithms using $m = 1$, $n = 4$ and $AR = 5$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers improved fairness performance while maintaining a competitive blocking probability compared to Semi-flex.

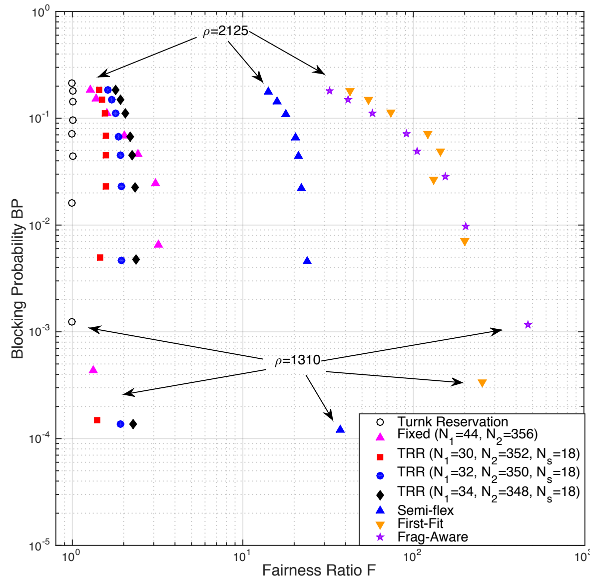

Fig. 10. Blocking probability (BP) versus fairness (F) for known RSA algorithms with $m = 1$, $n = 2$ and $AR = 0.2$. The range of traffic load (ρ) is from 1310 to 2125.

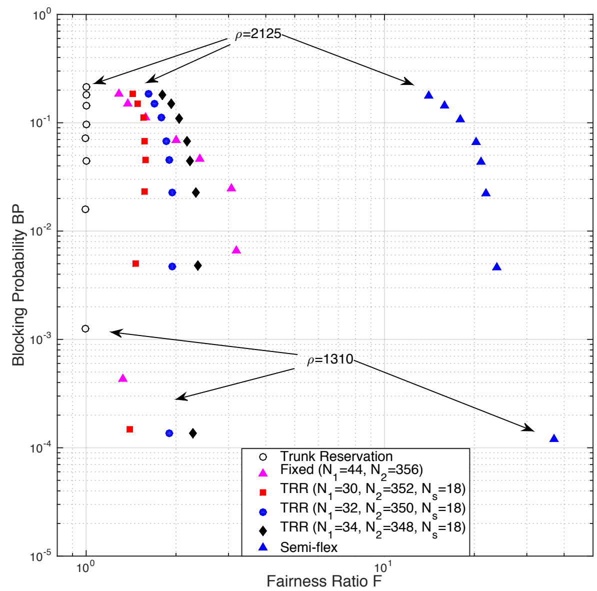

Fig. 11. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 2$ and $AR = 0.2$. The range of traffic load (ρ) is from 1310 to 2125.

J. $m = 1,\ n = 4,\ AR = 0.2$

Fig. 16 shows the blocking probability versus fairness indicator for three RSA algorithms using $m = 1$, $n = 4$ and $AR = 0.2$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed and Semi-flex. In this case, the TRR algorithm is not shown since there is no cases which satisfy the constraint, i.e, the maximum number of available slice blocks for group 1 demands $((N_1 + N_s)/m)$ is chosen to match the maximum number of available slice blocks for group 2 demands $((N_2 + N_s)/n)$.

K. $m = 1,\ n = 8,\ AR = 1$

Fig. 17 shows the blocking probability versus fairness indicator for four RSA algorithms using $m = 1$, $n = 8$ and $AR = 1$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers improved fairness performance compared to Semi-flex by about one order of magnitude while maintaining a competitive blocking probability

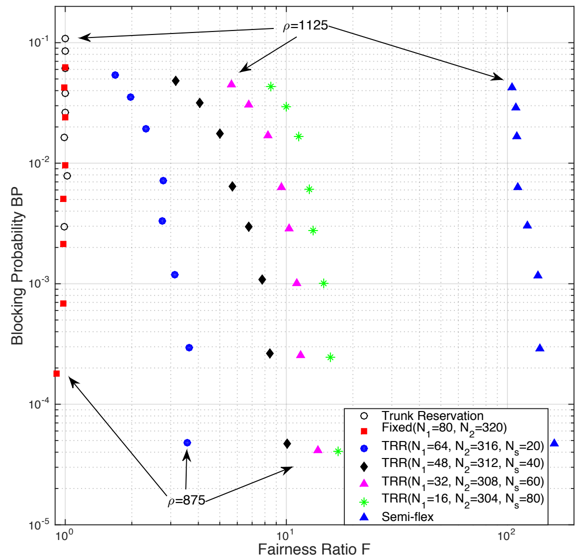

Fig. 12. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 4$ and $AR = 1$. The range of traffic load (ρ) is from 875 to 1125.

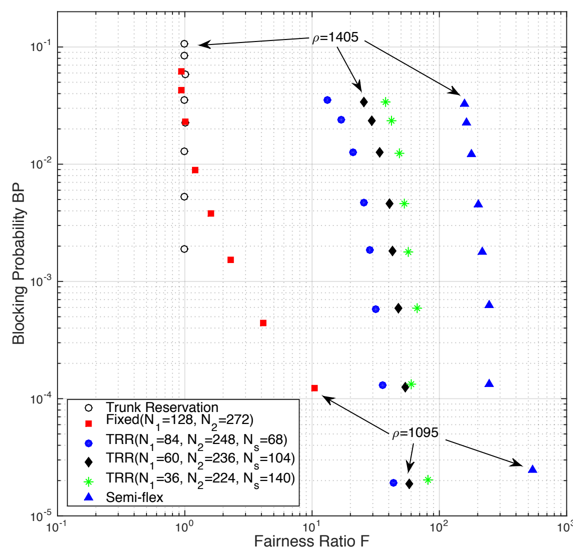

Fig. 13. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 4$ and $AR = 2$. The range of traffic load (ρ) is from 1095 to 1405.

when compared to Semi-flex, because TRR allows a controlled amount of slices to be statistically multiplexed between from group 1 and group 2. In the Fixed algorithm, the number of slices reserved to group 1 demands (N_1=48) is relatively larger than the number of slice blocks reserved to group 2 demands (N_2/8=352/8=44), due to the integer rounding required in this case. Recall that any uneven assignment of slices in Fixed favors group 1 demands.

L. $m = 1$, $n = 8$, $AR = 2$

Fig. 18 shows the blocking probability versus fairness indicator for four RSA algorithms using $m = 1$, $n = 8$ and $AR = 2$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers not only improved fairness performance compared to Semi-flex by about one order of magnitude, but also offers better blocking probability compared to Semi-flex.

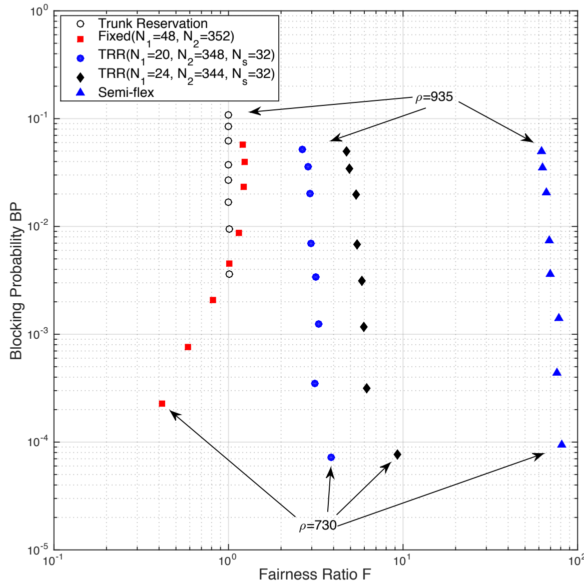

Fig. 14. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 4$ and $AR = 0.5$. The range of traffic load (ρ) is from 730 to 935.

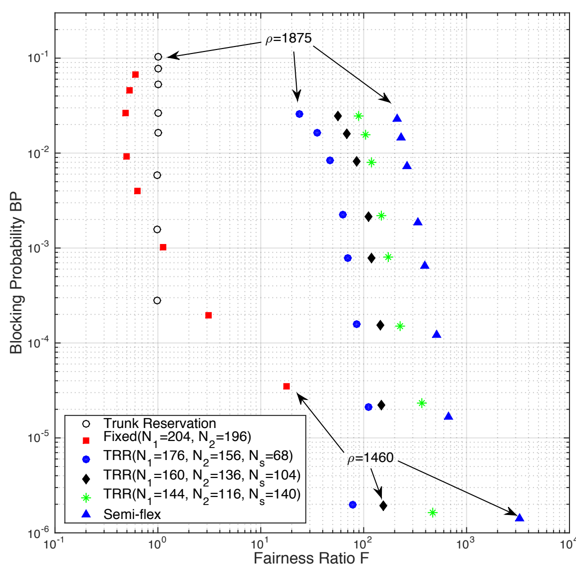

Fig. 15. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 4$ and $AR = 5$. The range of traffic load (ρ) is from 1460 to 1875.

M. $m = 1,\ n = 8,\ AR = 0.5$

Fig. 19 shows the blocking probability versus fairness indicator for four RSA algorithms using $m = 1$, $n = 8$ and $AR = 0.5$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers improved fairness indicator and offers better blocking probability compared to Semi-flex by about one order of magnitude. For the Semi-flex and TRR, the F indicator shows an oscillating pattern in the 10^1 to 10^2 range for the shown BP range.

N. $m = 1,\ n = 8,\ AR = 5$

Fig. 20 shows the blocking probability versus fairness indicator for four RSA algorithms using $m = 1$, $n = 8$ and $AR = 5$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed, Semi-flex and TRR. TRR offers improved fairness performance while maintaining a competitive blocking probability compared to Semi-flex.

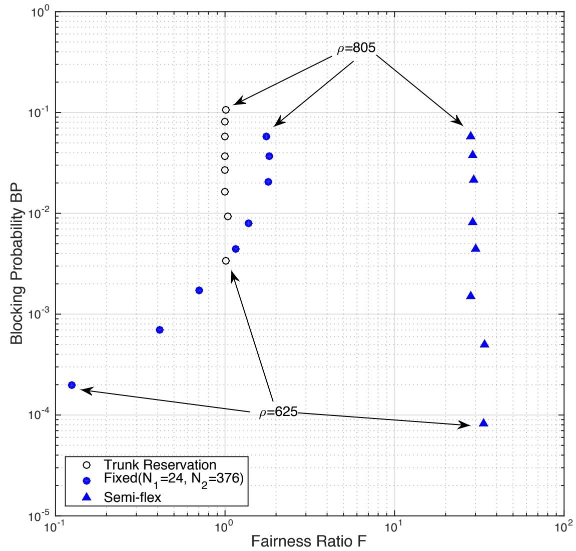

Fig. 16. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed and Semi-flex with $m = 1$, $n = 4$ and $AR = 0.2$. The range of traffic load (ρ) is from 625 to 805.

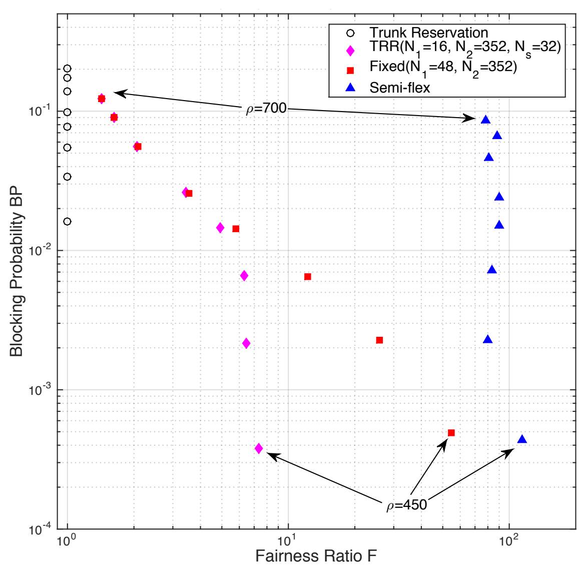

Fig. 17. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 8$ and $AR = 1$. The range of traffic load (ρ) is from 450 to 700.

O. $m = 1,\ n = 8,\ AR = 0.2$

Fig. 21 shows the blocking probability versus fairness indicator for the three RSA algorithms using $m = 1$, $n = 8$ and $AR = 0.2$. Each point in the chart refers to a particular offered load value, resulting in lower blocking as load decreases. From left to right (increasing values of F), the chart shows Trunk Reservation, Fixed and Semi-flex. In this case, the TRR algorithm is not shown since there is no cases which satisfy the constraint, i.e, the maximum number of available slice blocks for group 1 demands $((N_1 + N_s)/m)$ is chosen to match the maximum number of available slice blocks for group 2 demands $((N_2 + N_s)/n)$.

IV. Conclusion

A comprehensive way to evaluate the performance of RSA algorithms is to jointly consider the overall blocking probability experienced by the connection demands along with how fairly each demand type is handled by the algorithm. This approach is particularly meaningful in two-rate EONs, in which two groups of demands are serviced: group 1, requiring 1 slice of spectrum and group 2, requiring n slices. Seven RSA algorithms were analyzed using this pair of key performance indicators jointly,

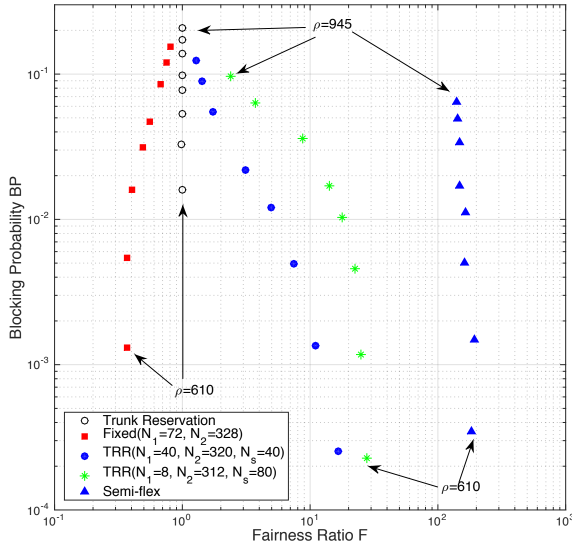

Fig. 18. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 8$ and $AR = 2$. The range of traffic load (ρ) is from 610 to 945.

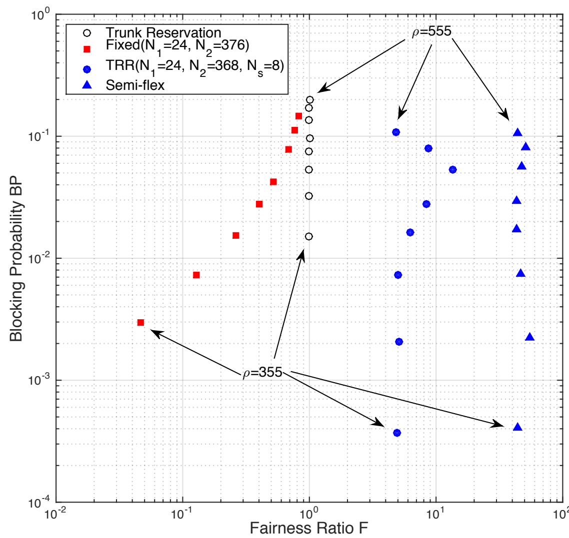

Fig. 19. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 8$ and $AR = 0.5$. The range of traffic load (ρ) is from 355 to 555.

illustrating how some of these algorithms favor blocking over fairness or vice versa. From the simulation results, we know that the greater the difference of requested slices between two groups and/or the more demands of group 2 than those of group 1 exist in the system, the better performance of TRR compared to well known RSA algorithms. The next step in this study is to extend the RSA algorithms' evaluation based on two performance indicators to other EONs that employ more than two rates (or groups of demands).

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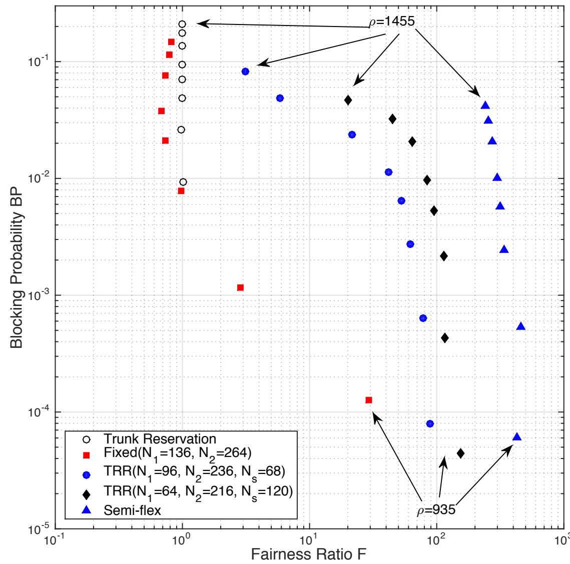

Fig. 20. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed, TRR and Semi-flex with $m = 1$, $n = 8$ and $AR = 5$. The range of traffic load (ρ) is from 935 to 1455.

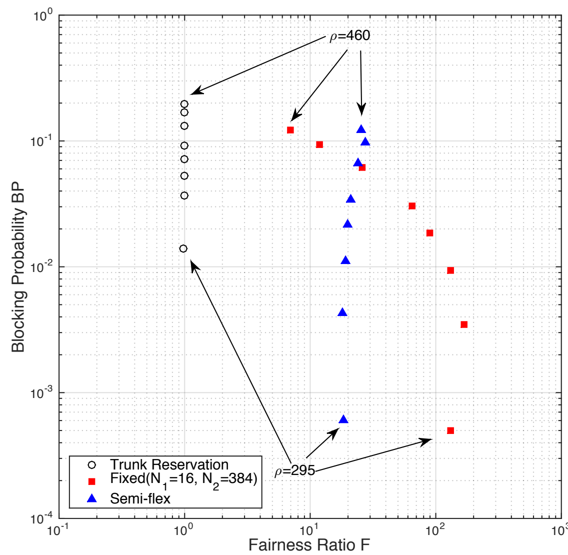

Fig. 21. Blocking probability (BP) versus fairness (F) for Trunk Reservation, Fixed and Semi-flex with $m = 1$, $n = 8$ and $AR = 0.2$. The range of traffic load (ρ) is from 295 to 460.

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