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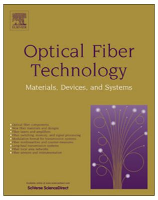

Regular Articles

An improved scheduled traffic model utilizing bandwidth splitting in elastic optical networks

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ABSTRACT

The surge of traffic in today's networks gave birth to elastic optical networking paradigm. In this paper, first we propose to use the scheduled traffic model (STM) in elastic optical networks (EONs) to ensure guaranteed availability of resources to demands which enter into the network with a predetermined start and end times. In optical networks, such demands are referred to as scheduled lightpath demands (SLDs). To increase the amount of bandwidth accepted in network, next we introduce a time aware routing and spectrum assignment (TA-RSA) approach. We observed that provisioning of bulky SLDs has become more challenging in EONs due to enforcement of RSA constraints. To address this challenge, we improve the proposed STM and designed three heuristics for its implementation in EONs. In this work, we collectively refer to these heuristics as bandwidth segmented RSA (BSRSA). The improved STM (iSTM) allows splitting of SLDs in bandwidth dimension by utilizing the knowledge of attributes viz. demand holding time, overlapping in time and bandwidth requested by SLDs. Our numerical results show that BSRSA consistently outperformed over TA-RSA under all distinctive experimental cases that we considered and achieved fairness in serving heterogeneous bandwidth SLDs. The impact of splitting on the number and capacity of transponders at nodes is also gauged. It is observed that ingenious splitting of demands increases the number of resources (on links and nodes) used, and their utilization, leading to an increase in bandwidth accepted in the network.

1. Introduction

With the exponential growth of traffic, optical networks are experiencing a paradigm shift. This growth is fueled by various bandwidth hungry applications such as e-science, grid computing, collaborative learning through audio-visual aids, etc. and it will soon cross the zettabyte threshold [1]. Recently, the elastic optical networks (EONs) have emerged as a promising paradigm to accommodate this torrent of traffic with a high spectral efficiency [2]. EONs employ a flexible grid which divides complete optical spectrum into a number of smaller units known as frequency slots (FSs). To provision a connection request (CR), the problem of searching a route and allocating desired number of FSs on each link of the route is called as routing and spectrum assignment (RSA) in EONs [3]. The solution to the RSA problem must follow two constraints, namely, spectrum continuity and contiguity. The spectrum continuity constraint states that a lightpath must use the same indexed slots on each traversed link; however, the contiguity constraint requires that slots assigned to a demand must be consecutive in the spectrum. Authors in [4] discussed various aspects of RSA problem in detail.

In today's bandwidth competitive environment, the objective of network operators has become threefold: accepting a huge volume of bandwidth in the network, efficient utilization of available resources and achieving significant gain in revenue with a high degree of customer satisfaction. Moreover, customers demand a guaranteed availability of resources when a CR arrives in the network. In EONs, allocating resources to a CR immediately when it arrives in network seems an obvious choice to operators for designing their network. This is referred to as dynamic provisioning of resources [5]. However, in its original form this technique cannot promise guaranteed availability because of the frequently changing load conditions on links. For example, consider a scenario where a virtual classroom is setup for one year course. The lectures are scheduled everyday from 10:00 to 14:00 h which is the guaranteed availability period for this application. If the operator is relying on dynamic provisioning then it has to setup this connection everyday at 10:00 h when CR arrives in the network and release it at 14:00 h. Now suppose someday, the requested bandwidth is not available due to heavy load in the network at 10:00 h and

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operator have to block the CR. This leads to poor customer satisfaction and a significant loss of revenue to the operator.

The solution to this problem is to use scheduled traffic model (STM) [6]. STM is a promising model to be used in the provisioning of CRs for which the start and end times along with their bandwidth requirement are known ahead of time. Such CRs are referred to as scheduled lightpath demands (SLDs) [7]. These demands are scheduled on the basis of prior information about their setup and tear down times. However, a great deal of work has been reported in literature considering STM, in reference to conventional fixed-grid optical networks [6–12]; to the best of our knowledge, this model has not yet been implemented in EONs.

In this paper, we propose to use STM in EONs for the provisioning of SLDs. Due to the use of flexible grid, EONs can easily accommodate demands having heterogeneous bandwidth requirement. However, in addition to the inherent knowledge of bandwidth requested by various demands, we wish to leverage the knowledge of time dimension of SLDs in EONs to achieve significant gain in terms of the amount of bandwidth accepted.

Initially, we present a time-aware RSA (TA-RSA) mechanism incorporating STM to EONs. TA-RSA takes into account the time-disjointness property of SLDs while performing RSA. We then compare the performance of TA-RSA with the traditional RSA approach used in EONs. We refer to this traditional RSA approach as time-unaware RSA (TU-RSA). Though TA-RSA outperformed TU-RSA by accepting a significantly large amount of bandwidth in the network, provisioning bulky SLDs in EONs is more challenging than it was in fixed-grid optical networks due to the enforcement of RSA constraints such as spectrum continuity and contiguity.

To address this challenge, we improve STM such that the effect of these RSA constraints is minimized and the time dimension of STM is efficiently utilized. In the improved STM (iSTM), SLDs are split in bandwidth dimension. To perform splitting, iSTM utilize the knowledge of bandwidth and time dimensions. In order to implement the iSTM, we propose three heuristics. We refer to these three heuristics collectively as bandwidth segmented RSA (BSRSA) strategy. We use the sliceable bandwidth variable transponder (SBVT) model proposed in [13] to divide the bandwidth of a demand into a number of chunks. We refer to these chunks as flows in this work. It has been observed that splitting the demands which require huge amount of bandwidth and have longer holding time (i.e., the duration for which a SLD remains active in network) is beneficial to increase throughput of the network. Simulation results demonstrate that proposed heuristics achieve fairness in serving demands with heterogeneous bandwidth and time requirements. The effect of proposed heuristics on the capacity and number of transponders utilized is also investigated.

The remainder of this paper is structured as follows: a brief review on STM, and the techniques used for decomposition of demands are presented in Section 2. Section 3 presents the formulations pertaining to the provisioning of SLDs along with the proposed heuristics. In Section 4, the numerical simulation setup and results are reported. Finally, Section 5 concludes the paper.

2. Related work

STM was proposed by authors in [7]. Demands under STM overlap in time. This gives the operator a freedom to assign same resources to other demands which are disjoint in time. This is known as time disjointness property of SLDs. In literature this property has been used to achieve various objectives in the fixed-grid optical networks.

Authors in [8–10] used the time disjointness property to minimize the required number of network resources; however authors in [11] utilized this property to minimize congestion in the network. In [12] authors exploited the time disjointness of SLDs to maximize the number of demands established. Since STM is a traffic matrix based model, i.e., the complete set of SLDs is known a priori, SLDs can be ordered before the provisioning to yield good results [6].

In the present work, under the iSTM, SLDs are decomposed with respect to their requested bandwidth into sub-parts. In [14], authors suggested the use of control plane for the splitting of demands. Once the splitting of a demand is done, each sub-part of the demand is assigned a bandwidth variable transponder (BVT) that is idle in the low load scenario. In this approach, decision of splitting requires prior knowledge of the available resources.

A split-spectrum enabled RSA (SSRSA) approach has been discussed in [15] for the SS-enabled EON. The aim of this provisioning approach is to minimize the splitting of demands and the spectrum fragmentation. SSRSA used single path to route all the parts of a demand which increased the blocking of connections. In [16], authors solved this problem under SS-enabled EONs by considering modulation format and multipath routing. Under the assumptions considered in the work, authors suggested the use of BVT based implementation, as it appeared more cost effective. However, contrary to this, authors in [17] demonstrated that with respect to the total transponder cost, SBVTs [13] are three times cost effective than BVTs. In the light of the fact that the capacity of SBVTs can be efficiently utilized as they can serve multiple lightpaths belonging to different s-d pairs in parallel and the cost analysis presented in [17–19], we prefer to use SBVTs over BVTs in this work for the purpose of splitting the flow belonging to a demand into multiple flows.

In addition to these proposals, authors in [20] have categorized the BVTs on the basis of their slicablility feature as: non-slicable BVT, fully sliceable BVT, and partially sliceable BVT. The non-slicable BVT is the basic BVT equipped with grooming capability to improve the transponder utilization. With the help of simulation results, authors demonstrated that significant power savings can be achieved using SBVTs at the cost of more power consumption by amplifiers due to the increased number of guard bands during slicing. In [21] authors proposed a heuristic to perform RSA using multi-wavelength SBVT. Their simulation experiments demonstrated the effectiveness of the scheme on the metric of blocking probability.

3. Provisioning scheduled lightpath demands

In this section, the nomenclature used in algorithms for provisioning of SLDs is presented. Furthermore, we define several constraints and design metrics used in the performance evaluation of proposed BSRSA. The subsections cover detailed discussion on the proposed heuristics.

We consider the physical network topology $G(N, L, F)$ representing EON, where N is the set of nodes, L is the set of links, and F is the set of FSs on each fiber link $l \in L$. A set of SLDs $R(s, d, B, \alpha, \beta)$ where s represents the source node, d represents the destination node and $(s, d) \in N$, B represents the bandwidth (in Gbps) requested by SLDs, α and β represent the setup time and tear down time of a SLD, respectively such that $\beta \geqslant \alpha$. We assume that the time is slotted. The set of time slots is indicated by T such that each slot is one hour long in time (i.e., $|T| = 24$). The set of candidate paths for each SLD present in R is represented by K. To perform RSA for each SLD, k candidate paths are pre-computed. Since BSRSA allows multiple flows belonging to a demand to be routed through different paths, a boolean variable MP_r is set to 1, if $r \in R$ requires multipath routing, otherwise 0.

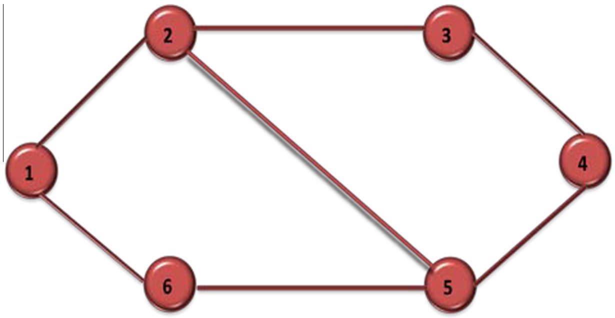

Fig. 1. Test topology with 6 nodes and 7 links to illustrate provisioning of SLDs.

Table 1
Example to demonstrate provisioning of SLDs in EONs with $|F| = 6$.

R_r	s_r	d_r	F_r (in slots)	α_r	β_r	Route assigned	Slots assigned
R_1	4	6	2	10:00	14:00	4-5-6	(1,2),3
R_2	3	6	5	16:00	20:00	3-4-5-6	(1-5),6
R_3	2	6	1	11:00	16:00	2-5-6	Blocked
R_4	1	5	1	02:00	06:00	1-6-5	(1),2

For the purpose of spectrum assignment, in all the heuristics, the bandwidth B_r requested by a SLD r, is converted into F_r, i.e., the number of FSs required by the SLD r as follows:

$$F_r = \lceil B_r/(f_w * M) \rceil \tag{1}$$

where f_w represents the slot width (in GHz) and M represents the number of bits used in the modulation format under consideration. If a FS, $f \in F$, on link $l \in L$, is assigned to the SLD $r \in R$ in time period $(b,t) \in T$ then $FL^{b,t}_{f,l,r}$ takes the value 1, otherwise 0. An FS on a link cannot be allocated to more than one lightpaths routed over the link at a time instant. That is,

$$FL^{b,t}_{f,l,r_i} + FL^{b,t}_{f,l,r_j} = 1 \; \forall f \in F, \forall l \in L, (r_i, r_j) \in R \text{ and } (b,t) \in T \tag{2}$$

However, a slot can be allocated to more than one demand if the two demands are disjoint in time i.e., their setup and tear down times do not conflict with each other. The Eq. (2) represents spectrum non-overlapping constraint with respect to time.

In this work, we have considered two types of transponders: BVTs and SBVTs. BVTs are utilized in TU-RSA and TA-RSA heuristics as these heuristics do not use splitting; however, in the case of BSRSA, SBVTs are used. The variable T_{type} is used to denote the category of the transponder used by a heuristic. It may take the value 'b' to represent BVT and 's' when SBVTs are used at the nodes. Let, C_g denotes the capacity of an (S)BVT in Gbps. In this work, we have assumed $C_g = 400$ Gbps [18]. C_g can be converted into equivalent FSs by replacing B_r with C_g in Eq. (1) and we represent the obtained value as C_f. We have assumed that an SBVT is virtually divided into several low capacity BVTs and we refer to them as sub-transponders (S-TSPs) throughout the text. The value of S represents the number of S-TSPs belonging to an SBVT. Since the division of an SBVT into S-TSPs is virtual, the number of S-TSPs can vary within a range such that the sum of the capacity of all the S-TSPs should not exceed C_g or C_f [19,22]. Therefore, in this work S may take the value such that $1 \leqslant S \leqslant 4$. Thus, a BVT is the type of transponder for which $S = 1$. A variable CS_f denotes the capacity of an S-TSP in terms of FSs. CS_f depends upon C_f and S [23].

The proposed heuristic BSRSA splits incoming SLDs in bandwidth with respect to F_r into various flows and then RSA is performed for each flow, individually. The number of flows in which a SLD r is being split is denoted by $NFlow_r$ such that $NFlow_r \leqslant S$. A vector $SFlow_j$ denotes the size of jth flow in terms of FSs such that $1 \leqslant j \leqslant NFlow_r$. The sum of all FSs allocated to each flow belonging to a SLD should be equal to

$$\sum_{j}^{NFlow_r} SFlow_j = F_r + (G * NFlow_r) \tag{3}$$

This represents the flow size constraint. In Eq. (3), G indicates the number of FSs used as guard band. The size of G adversely affects the performance of BSRSA as total number of FSs used in guard bands is equal to the number of flows. We have considered $G = 1$ in this work in order to minimize such an adverse effect. The value of $SFlow_j$ is also bound by CS_f such that $SFlow_j \leqslant CS_f$.

There is a tuning parameter ω in BSRSA. On the basis of this ω, a flow threshold, F_{th} is computed which plays a key role in deciding the value of S corresponding to BSRSA and $NFlow_r$ and $SFlow_j$ corresponding to each SLD. Next, some metrics are presented that we used in performance evaluation of the proposed strategies.

Resource utilization ratio (RUR): It is defined as the ratio of the network capacity utilized to the number of SLDs accepted in the network.

Spectrum utilization ratio (SUR): It is the ratio of the number of FSs utilized to the total spectrum available in the network.

Since, TU-RSA is well known approach which is being widely used with reference to static traffic in EONs; we omit the discussion regarding it due to the space limitation, and proceed with TA-RSA. Let Fig. 1 and Table 1 show the representative test topology and attributes, respectively to demonstrate the process of RSA for SLDs in EONs. It is assumed that all the FSs on all links are available and first fit spectrum assignment is used. When R_1 arrives in the network, it will be assigned spectrum on FSs (1-2) and one additional slot (3), for guard band on the links 4-5 and 5-6 for 10:00 to 14:00 h. For next SLD R_2, the route 3-4-5-6 is selected. R_1 and R_2 have two links in common and since they both do not conflict in time, R_2 can use FSs (1-3) on these links. Hence, R_2 is assigned FSs (1-6) on all the links of the route. When R_3 enters into the network, route 2-5-6 is selected for it. Since all the FSs on the link 5-6 are exhausted and because R_3 is conflicting in time with the previous two SLDs, the resources on link 5-6 cannot be reused for this SLD. Thus, R_3 could not be accepted in the network. Next, SLD R_4 arrives which does not conflict with R_1 and R_2. Thus, it can reuse the resources on link 6-5 and assigned slots as indicated in the table.

3.1. Time-aware routing and spectrum assignment (TA-RSA) heuristic

The algorithm for TA-RSA is shown in Table 2. An SLD from the set R is first considered, a path from the available set of candidate paths K is then selected. Such a path should have the desired number of resources on nodes as well as links throughout the path. In the process of selecting route and assigning FSs, TA-RSA takes spectrum contiguity and continuity constraints under consideration. Next, to take the advantage of prior information regarding the setup and tear down time of SLDs, time scheduling is performed. For time scheduling of incoming SLDs, in the next step of TA-RSA, time disjointness of SLDs as enforced by the constraint mentioned in Eq. (2) is checked. To assign the spectrum, TA-RSA used first-fit approach in which spectrum is scanned from the lowest ordered available FS to the highest ordered available FSs. A frequency slot can be reused for those SLDs which are disjoint in time. Similar to the FSs on a link, a transponder on a node i.e., BVT in this case, can be reused, if the request confers with the time disjointness.

During the extensive simulation experiments, we analyzed that SLDs having longer holding time (HT) and larger bandwidth

Table 2
Algorithm for TA-RSA.

Input: Graph G(N, L, F) representing EON, a SLD $r \in R(s, d, B, \alpha, \beta)$, a set of candidate paths K, transponder capacity C_f and the category of transponder to be used T_{type}
Output: Route and frequency slots assigned to all SLDs accepted in the network

```
Perform RSA using single path routing
if route is found for $r$ then
    Update link status
    if $T_{type}$ = 'b' then
        Update the BVT capacity and the number of available BVTs
    else
        Update the SBVT capacity and the number of available sub-transponders
    end if
    Accept the SLD $r$
else
    Block the SLD $r$
end if
return
```

requirement (referred to as voluminous or bulky SLDs) occupy large number of resources for a longer duration. Hence, such SLDs are more likely to conflict in time with other SLDs. This behavior is resulting due to the enforcement of spectrum continuity and contiguity constraints at the time of performing RSA. Thus, with an increase in load, the number of available FSs decreased in network under TA-RSA. These available FSs may not be sufficient to provision upcoming SLDs and are subjected to blocking of SLDs in network. In this work, blocking due to the lack of resources at nodes is not considered in all the proposed heuristics, because we have assumed that there is sufficient number of transponders, i.e., (S)BVTs are available at each node in the network [16].

3.2. Bandwidth segmented routing and spectrum assignment (BSRSA) heuristic

To significantly reduce the deleterious effects of voluminous SLDs caused due to the presence of RSA constraints in EONs, the proposed iSTM utilizes bandwidth splitting. We propose three heuristics to implement such STM and collectively refer to them as BSRSA strategy. BSRSA splits SLDs into multiple flows in the bandwidth dimension using SBVT and then performs RSA for each flow. BSRSA can adopt either single-path routing or multipath routing. However, BSRSA restricts each individual flow belonging to a demand to a single route until sufficient number of FSs is not available on that route. We improve the existing STM by allowing splitting of SLDs in bandwidth dimension by exploiting the knowledge of HT, time conflict between SLDs, and requested bandwidth of SLDs.

Table 3 shows the algorithm for BSRSA heuristic. A set G containing the topology information, a set of SLDs R, a set K of candidate paths, SBVT capacity C_f, and certain parameters specific to the three splitting heuristics are passed as input to BSRSA algorithm. BSRSA works in two phases. First phase is the pre-computation phase. In this phase, the flow threshold, and other parameters related to the number and capacity of S-TSPs belonging to an SBVT are computed. In the second phase, RSA is performed by splitting incoming SLDs into a number of flows. Step 4 holds the key to BSRSA. At this point, under the iSTM, the operator has the flexibility to choose any of the three proposed strategies namely, BSRSA in time dimension (BSRSA-T), BSRSA in time dimension with time conflict (BSRSA-TTC) and BSRSA in bandwidth and time dimension (BSRSA-BT). Each of these heuristics utilizes the information regarding time and bandwidth or any of the two to arrive at the decision regarding the splitting of SLDs. Hence, HT, conflict count (CC), and bandwidth are three key attributes to facilitate the efficient provisioning of SLDs. Heuristics discussed in subsequent subsections will highlight the use of these attributes.

Once the operator has decided on a heuristic, BSRSA then selects a SLD from the set R and analyze it based on its characteristics (i.e., bandwidth, HT, and CC) whether the SLD needs to be split. If the SLD seems to be a suitable candidate for splitting, BSRSA computes the number of flows $NFlow_r$ as mentioned in Step 8 of the algorithm. The flow threshold imposes a limit on the number of flows in which a SLD can be split. In later steps of the algorithm, size of a flow $SFlow_j$ is computed. It is bounded by the flow size constraint given in Eq. (3). The flow size constraint ensures that the sum of FSs allocated to all the flows belonging to a SLD should not exceed the number of FSs requested by SLD and the guard band requirement for each flow.

After deciding $SFlow_j$, RSA for the flow is performed by considering the single-path routing first. In this method, all the remaining flows must follow the same route as that of the first flow pertaining to a SLD. If it is not possible to route all the flows of a SLD through the same route then BSRSA will adopt multipath routing. Thus, with multipath routing, BSRSA prevents a SLD from blocking, when it could not be served with single-path routing. Though, BSRSA is using multipath routing, for the purpose of simplicity, consideration of differential delay is out of the scope of this work [24]. To avoid unnecessary splitting of SLDs, BSRSA has the provision to serve in the basic TA-RSA mode also. This is the case when a SLD does not qualify for splitting under BSRSA.

At the time of performing routing, BSRSA also checks for the time disjointness of resources at the nodes and links of the route selected. This feature of BSRSA is similar to TA-RSA with respect to links. However, at the nodes, BSRSA checks the time disjointness at the S-TSP level. This means that individual S-TSPs are considered as independent BVTs here and an S-TSP can be reused if the SLDs using it are not conflicting in time. Due to this feature, BSRSA could efficiently utilize the resources in terms of reuse of transponders.

3.2.1. BSRSA in time dimension (BSRSA-T)

The duration for which a SLD uses the resources, affects network performance. SLDs with longer HTs result in more blocking. This is because such SLDs prevent other SLDs from using the resources for a longer duration. This situation gets worse due to the enforcement of continuity and contiguity constraints while performing RSA. This problem could be minimized if such SLDs are split into multiple flows with respect to their bandwidth. BSRSA-T splits SLDs which are bulky in time i.e., their HT is longer than the mean HT ($\overline{RH}$) of all SLDs entering into network. This would reduce the amount of bandwidth carried by a flow at a particular instant pertaining to a SLD, thereby leaving more FSs to other SLDs.

3.2.2. BSRSA in time dimension with time conflict (BSRSA-TTC)

If two SLDs conflict in time domain, they cannot share spectral resources due to the time disjointness constraint. The prior knowledge of setup and tear down times of SLDs facilitate network operator to know the conflict count corresponding to each SLD. We define the *conflict count* as an indicator to the degree with which an SLD is conflicting with other SLDs in network. Large conflict counts along with the spectrum contiguity constraint contribute in deteriorating the performance of network. This combined effect reduces reuse of FSs present in spectrum thereby decreasing the spectrum efficiency. To overcome this problem, solution is to split the requested bandwidth of a SLD if its conflict count is higher than the mean conflict count ($\overline{CC}$) of all the SLDs present in the set R. This would improve the spectral efficiency of network.

3.2.3. BSRSA in bandwidth and time dimensions (BSRSA-BT)

The demands which require high bandwidth or demands which remain in the network for longer duration affect the performance of TA-RSA severely. Thus, the solution lies in breaking such demands into multiple flows. Splitting a bulky demand into bandwidth dimension would significantly increase the amount of accepted bandwidth in network. Therefore, in this strategy, only those SLDs which satisfy either of the two conditions are divided into multiple flows:

(i) The number of FSs required by a SLD, F_r is greater than the mean FS requirement ($\overline{RF}$).
(ii) The holding time, H of a SLD is longer than $\overline{RH}$.

An operator can employ any of the three heuristics as per the need. For example, if a large number of SLDs are having longer HTs then the operator may choose to use BSRSA-T while BSRSA-TTC can be preferred to encourage the reuse of spectrum. However, if the objective of operator is to increase the revenue by accommodating SLDs which are more demanding in terms of bandwidth and time, then BSRSA-BT could serve the purpose.

Since all the heuristics use pre-computed k-candidate paths, the time complexity of selecting a route will be $O(1)$. In TA-RSA, the spectrum allocation for a SLD can be done in $O(|F|.|E|)$, where $|F|$ represents the number of FSs on a link and $|E|$ is the number of links in the network. The three heuristics, BSRSA-T, BSRSA-TTC, and BSRSA-HT can take the decision to split an SLD into multiple flows in $O(1)$. After splitting an SLD into multiple flows, BSRSA has to perform spectrum allocation for all the flows individually. Hence, the time complexity of BSRSA for allocating the spectrum will be $O(NFlow.|F|.|E|)$ where $NFlow$ represents the number of flows belonging to an SLD in the network.

Table 3
Algorithm for BSRSA.

Input: Graph G(N, L, F) representing EON, a set of SLDs $R(s, d, B, \alpha, \beta)$, a set of candidate paths K, transponder capacity C_f, $\overline{RF}$,$\overline{RH}$ and $\overline{CC}$
Output: Route and frequency slots assigned to all SLDs accepted in the network

```
Phase I: Pre-computation
1. $F_{th} \leftarrow \lfloor \overline{RF}/\omega \rfloor$
2. $S \leftarrow \lfloor C_f/F_{th} \rfloor$
3. $CS_f \leftarrow \lceil C_f/S \rceil$
Phase II: Routing and spectrum assignment using SBVT
4. Select one of the three heuristics (BSRSA-T/BSRSA-TTC/BSRSA-BT)
5. Select an SLD $r \varepsilon R$
6. $MP_r \leftarrow 1$
7. if r requires splitting then
8.   $NFlow_r \leftarrow \lceil F_r/F_{th} \rceil$
9.   for j ← 1 to $NFlow_r$ do
10.      Compute SFlow(j)
11.      if $j > 1$ AND $MP_r = 1$ then
12.        Perform RSA using multipath routing
13.      else
14.        Perform RSA using single-path routing
15.        if j > 1 AND route is not found for j then
17.          goto Step 11
18.        end if
19.      end if
20. end for
21. if route is not found for any of the flows then
22.      Block the SLD r
23. else
24.      Update link status
25.      Update the SBVT capacity and the number of available sub-
         transponders
26.      Accept the SLD r
27. end if
28. else
29.   Call TA-RSA subroutine with r and $T_{type}$
30. end if
31. select next SLD from the set R
```

4. Simulation results and discussion

To implement all the proposed strategies and study their performance, a simulation program is developed in MATLAB. Information regarding network topology, traffic matrix and pre-calculated routes is supplied as input parameters to the program. To evaluate the performance of proposed strategies, we considered 14 nodes 21 links NSFNET network topology. All simulations were run on an Intel Core 2 Duo 2.20 GHz CPU with 4 GB RAM under Windows 7 environment. Following assumptions were made to conduct simulation experiments:

(i) SLDs are generated randomly under STM stating their setup and tear down times along with the specific line rates required by them.
(ii) The line rates required by SLDs are assumed to be 25 Gbps, 150 Gbps, and 250 Gbps and uniformly distributed among all SLDs present in set R.
(iii) The spectrum width is 3875 GHz and each slot in the spectrum is 12.5 GHz wide.
(iv) We assumed $M = 2$ to be used in Eq. (1) [25].
(v) Fixed alternate routing with three alternate routes is considered and for the computation of routes, k-shortest path algorithm is used.

In order to get a more realistic picture, five sets of the original traffic matrix were randomly generated. We have tested all the strategies on these sets and results reported in this section are average of these five different sets. When we compared TA-RSA with TU-RSA, it performed exceedingly well in terms of all the metrics as of interest. Due to the space limitation, instead of giving a detailed discussion, we summarized the results in the form of Table 4. As TA-RSA outperformed TU-RSA, from here onwards we use TA-RSA to serve as the benchmark while evaluating the performance of BSRSA.

The performance of all the strategies for the amount of bandwidth accepted in the network is shown in Fig. 2. BSRSA outperformed TA-RSA on this metric. Moreover, network capacity utilized by BSRSA in the process is also small. For example, BSRSA-TTC accepted 50.97% more bandwidth than TA-RSA by consuming 6.5% less spectral resources. On an average, amongst all the variations of BSRSA, BSRSA-TTC performed better while the performance of BSRSA-BT and BSRSA-T is nearly the same with respect to the amount of bandwidth accepted in the network.

The metric RUR indicates how efficiently resources are utilized in the network. Low RUR reflects efficient utilization of resources. It is quite obvious from Fig. 3 that as the number of SLDs in network increases, RUR decreases. The decrease in RUR is attributed to the rapid increase in number of SLDs accepted with respect to the network capacity utilized. Although, BSRSA-T is least resource efficient among the three heuristics; its performance in terms of the metric is 26.37% better than TA-RSA.

As Fig. 4 shows, in contrast to RUR, SUR increases with a gain in the number of SLDs for all strategies. This increase is attributed to the steady growth in the number of resources utilized as the number of SLDs grows in the network. Ideally, for a given strategy, low value of SUR reflects good efficiency as it indicates the amount of

Table 4
A comparison of TU-RSA and TA-RSA on various parameters.

Parameters	TU-RSA	TA-RSA
Accepted bandwidth (Tbps)	32.25	113.85
Number of BVTs used in the network	599	448
Number of fragmented FSs in spectrum	765	113
FS utilized over all links in the network	5717	6383

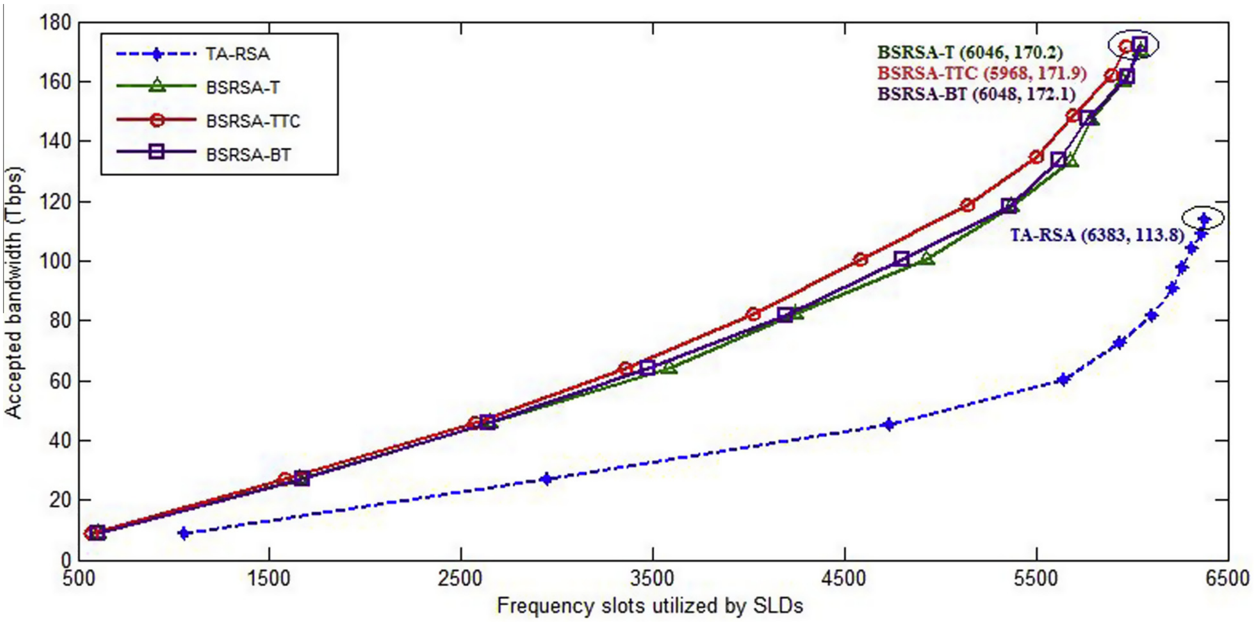

Fig. 2. Variation of bandwidth accepted with respect to the frequency slots utilized, as the number of SLDs arriving in the network increase.

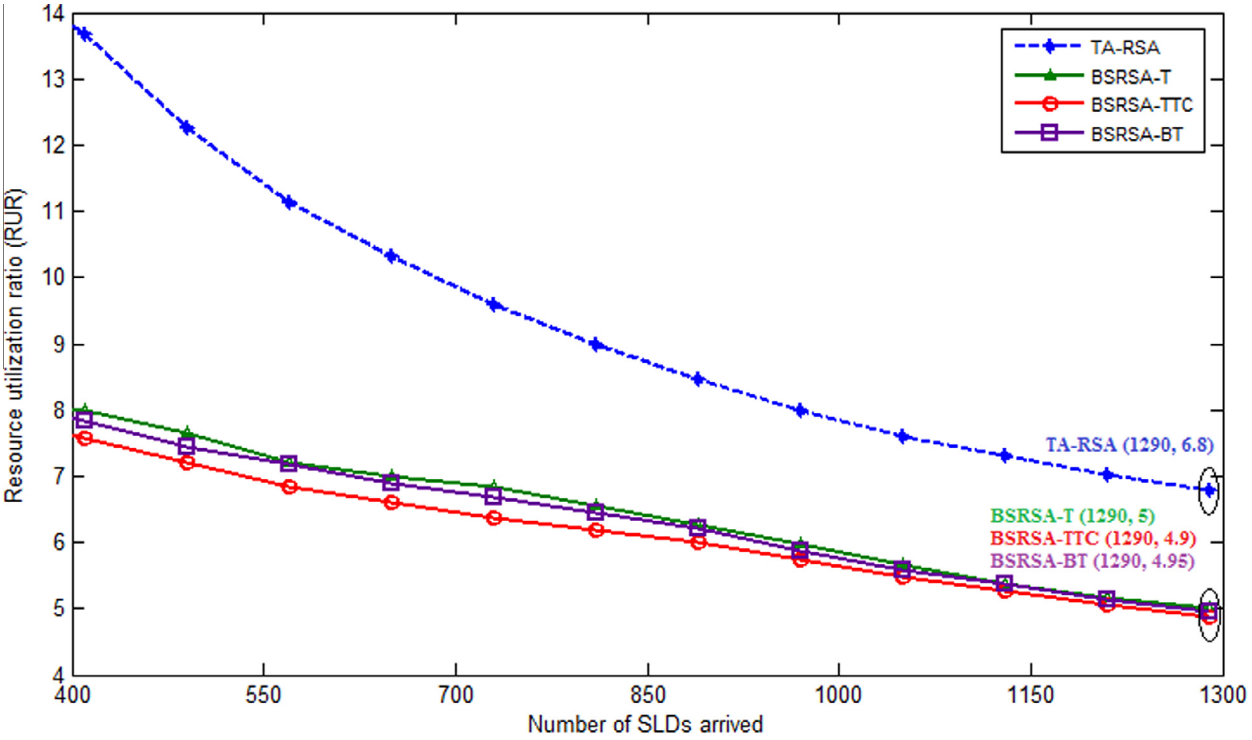

Fig. 3. Plot depicting the resource utilization ratio (RUR) corresponding to the number of SLDs arrived in network.

spectrum remaining free for the upcoming SLDs. SUR is minimum in case of BSRSA-TTC and maximum for TA-RSA. However, it is interesting to note that at high loads, the rate of increase of SUR tend to increase slowly for TA-RSA when compared with respect to BSRSA-T and BSRSA-TTC. This is due to the fact that the number of available resources to establish SLDs stagnates as load increases in TA-RSA. This triggers blocking of SLDs in the network.

Since in this work, we have considered the availability of resources in terms of the transponders at nodes; the impact of splitting on the number and capacity of transponders consumed is analyzed next. Splitting a connection into multiple flows and using multipath routing, both require additional guard bands. Due to splitting of SLDs, the number of guard bands increases and this number affect the capacity and number of transponders. Therefore, for the purpose of fair analysis of the transponders' capacity consumed by various strategies, we have deducted the amount of capacity that is used for guard bands. Fig. 5 indicates that TA-RSA accepted minimum amount of bandwidth. The capac-

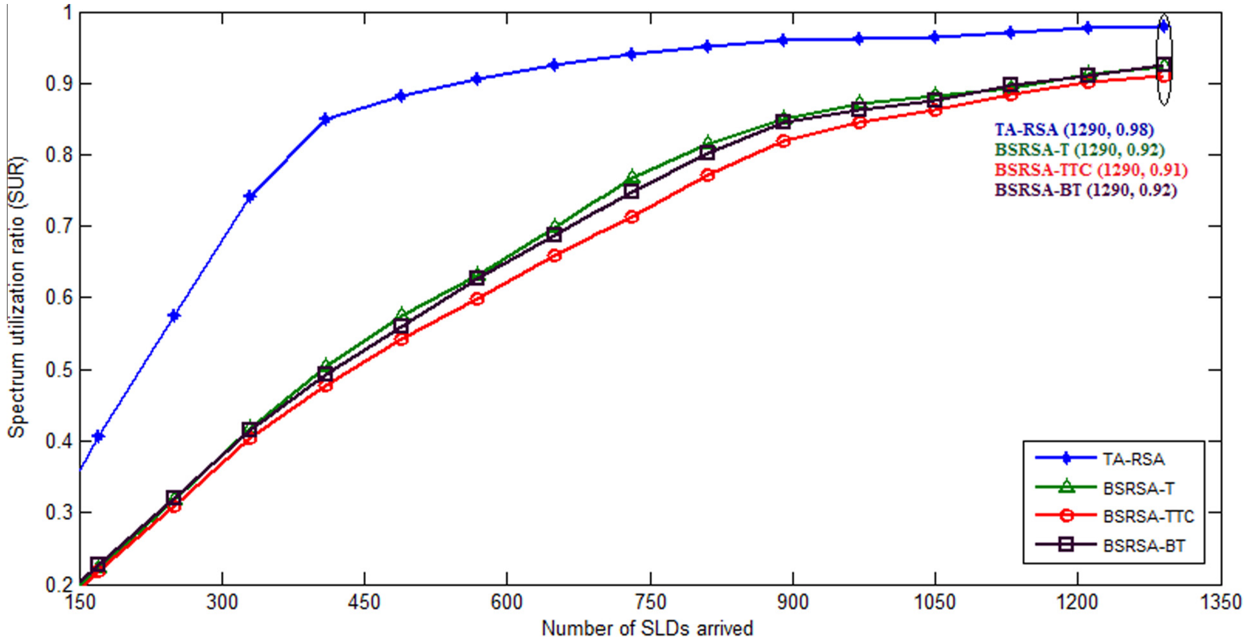

Fig. 4. Variation in the spectrum utilization ratio (SUR) with the number of SLDs arrived in network.

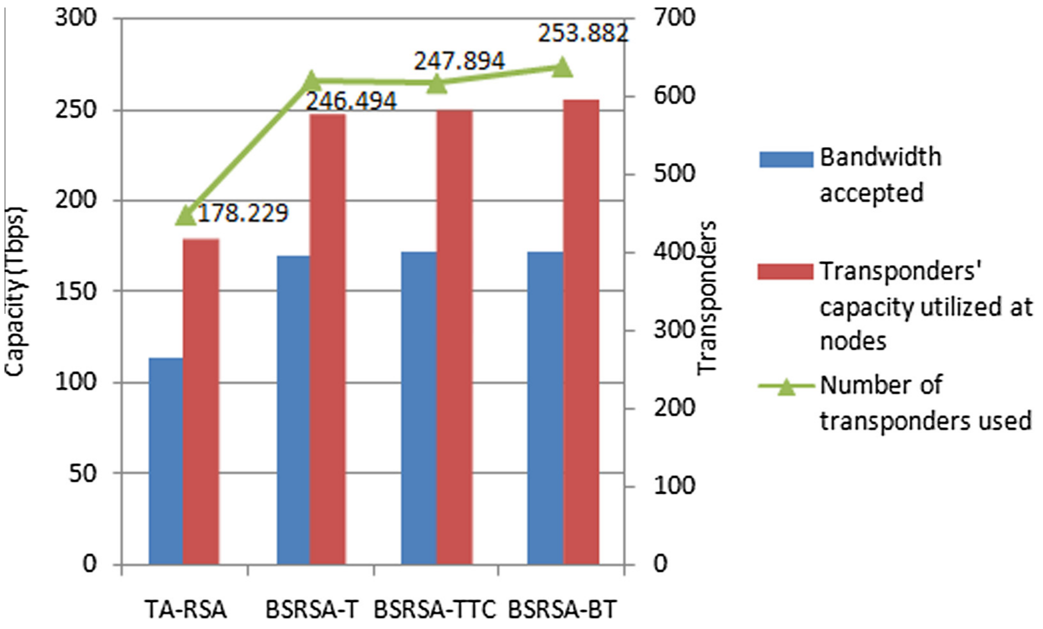

Fig. 5. Transponder capacity and number of transponders utilized along with the bandwidth accepted in the network.

ity of transponders utilized is also low. Since one BVT can serve only one SLD, the capacity of transponders could not be utilized efficiently in TA-RSA. Nevertheless using SBVTs, the number of transponders used by BSRSA-BT, BSRSA-T, and BSRSA-TTC is 42.41%, 38.62%, and 37.72% more than TA-RSA. Though all the variants of BSRSA utilized more number of transponders than TA-RSA, the utilization of transponders is significantly better in terms of the ratio of bandwidth accepted to the transponder capacity utilized. This is due to the reason that a sliceable transponder can serve more than one SLDs using individual sub-transponders present at it.

Fig. 6 provides a justification for the utilization of higher capacity and more number of transponders in BSRSA as compared to TA-RSA. Splitting a demand into multiple flows requires more number of transponders to be used for each flow. Similarly, multipath routing involves more number of nodes than single-path routing; it contributes more to the number of transponders utilized. In TA-RSA, SLDs are not split and there is no provision to route SLDs over multiple paths. Contrary to this, BSRSA-BT split 71.43% of SLDs accepted out of which 7.11% SLDs needed multipath routing. This being the sole reason for BSRSA-BT and others to consume more number of transponders than TA-RSA. The performance of BSRSA-TTC is better as it required the least, i.e., 30.82% SLDs to split and out of those only 13.34% SLDs needed multipath routing.

Since EON can accommodate heterogeneous bandwidth demands, it is important to observe the effect of proposed strategies on the fairness in accepting heterogeneous bandwidth SLDs in network. It is clear from Fig. 7 that various strategies favor the

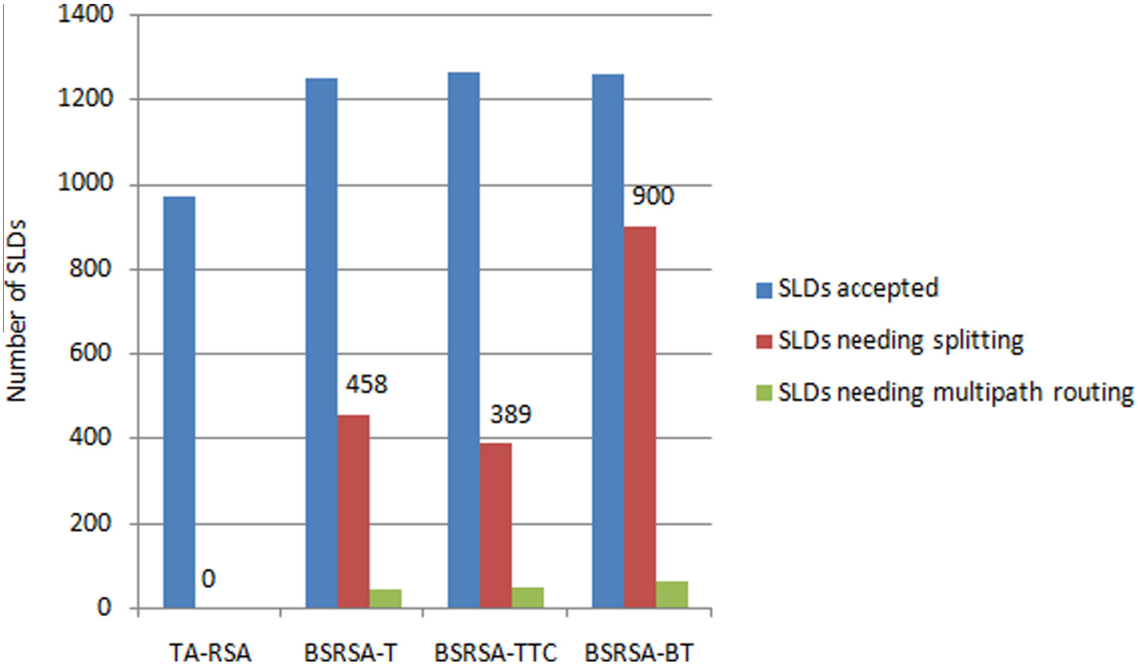

Fig. 6. A statistics on the number of SLDs accepted in network and the number of SLDs needing splitting and multipath routing.

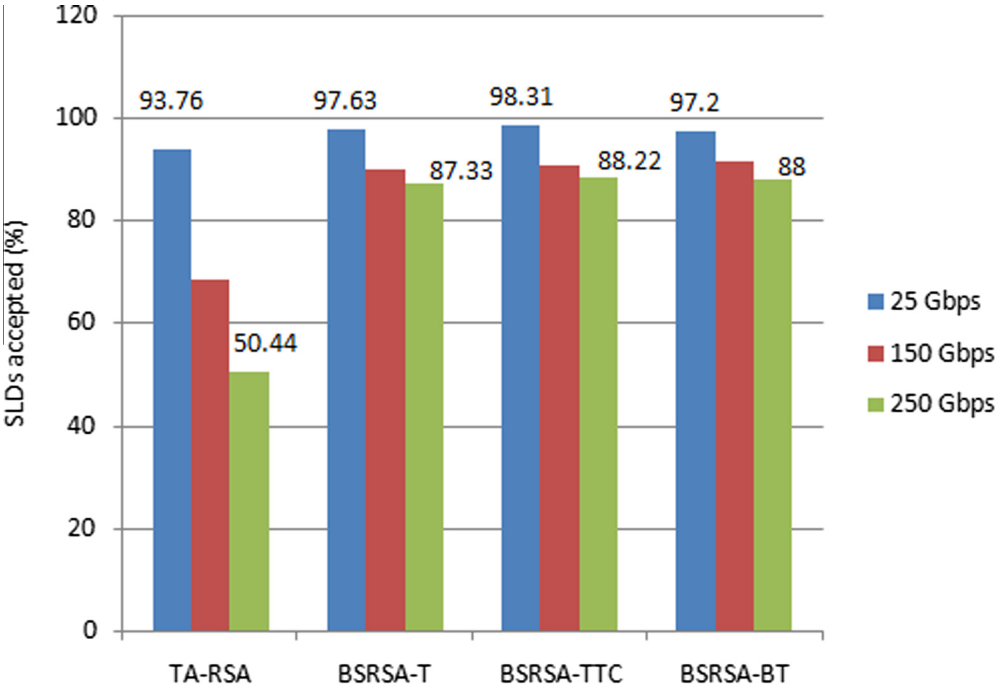

Fig. 7. Graph illustrating the percentage of SLDs accepted by various strategies corresponding to heterogeneous bandwidth SLDs with FS = 310 on each link.

acceptance of low bandwidth SLDs over high bandwidth SLDs. However, TA-RSA does not comply with the fairness between the two extremes of requested bandwidth in terms of the percentage of SLDs accepted in the network. This is due to a wide gap of 43.32% amidst the two extremes. This gap decreases continuously for BSRSA-T, BSRSA-TTC, and BSRSA-BT to 10.06%, 10.3%, and 9.2%, respectively. It is quite evident that BSRSA is fairer than TA-RSA in serving SLDs with different bandwidth requirements.

It is likely that SLDs coming into a real network differ in their HT requirement. Therefore, till now we presented all the results on random HT. However, to gauge fairness of the heuristics for variable HTs, we have also evaluated their performance for SLDs with fixed HT of 2 h, 4 h and 6 h as shown in Fig. 8. For a network, to accept a demand with high bandwidth is always a challenge. Due to this reason, we were particularly interested in analyzing the percentage of high bandwidth SLDs accepted by the proposed heuristics for different HTs. Hence, the results reported in Fig. 8 are for SLDs requesting 250 Gbps bandwidth. The trend of Fig. 8 indicates that as HT increases, the percentage of SLDs accepted in the network decreases. All the heuristics, individually have fol-

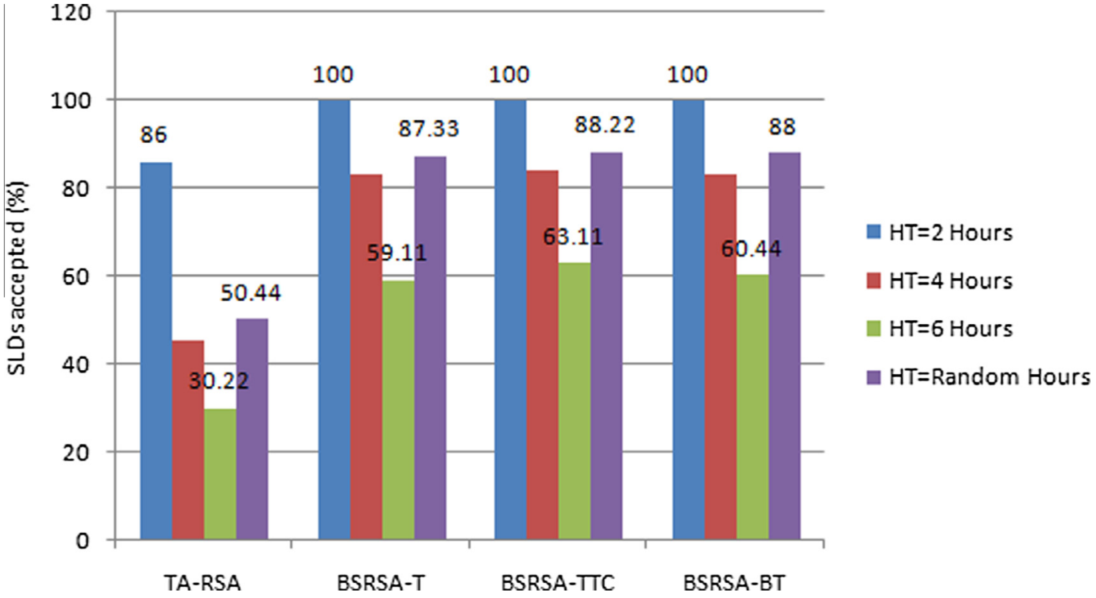

Fig. 8. Percentage SLDs accepted for different holding times (HTs) corresponding to the SLDs requesting 250 Gbps bandwidth.

lowed this trend. Nevertheless, it is interesting to note that this differs when TA-RSA is compared with BSRSA. On an average, BSRSA accepted 86%, 61.69%, 78.96%, and 62.59% more SLDs than TA-RSA for 2 h, 4 h, 6 h, and random HT respectively. This behavior results to the splitting of SLDs in BSRSA. Thus, justifying the need for splitting SLDs when STM is used in the network.

In this work, we have performed all simulations for three values of ω (i.e., 1, 2 and 4) and from the results obtained, we observed that the value of ω has a vital role in the splitting process because higher values of ω resulted in small F_{th}. This leads to excessive splitting and it results in high fragmentation and consumption of extra resources for providing the guard bands. An additional factor that proves to be costly in terms of resources is multipath routing which involves more number of nodes and thus more transponders are needed. Hence, splitting has to be judiciously used. In this work, we have reported results with $\omega = 1$ as it yielded best results.

Amongst all the proposed heuristics, BSRSA-TTC seemed to be a better choice. This is due to the fact that as the number of SLDs increase in the network, their conflict count also increases. In such a scenario, more SLDs will get blocked due to the enforcement of time disjointness constraint. Therefore, splitting of SLDs with the knowledge of their conflict count value, helped in achieving good performance for BSRSA-TTC than BSRSA-BT and BSRSA-T. The only odd that BSRSA-TTC faces is in terms of fairness in serving heterogeneous bandwidth SLDs, where its performance was mediocre amongst the others.

5. Conclusion

From our initial proposal, we have observed that due to the enforcement of RSA constraints, the provisioning of voluminous SLDs become very difficult in EONs. To meet this challenge, we have proposed an improved STM so as to leverage the capabilities of STM and EONs jointly, and increase the throughput of network. The results of the investigation demonstrate that splitting yields good performance because of efficient utilization of resources in the network. The splitting leads to better link utilization, and increase in the number and capacity of transponders available at the nodes. However results indicate that excessive splitting adversely affects the performance. Hence, in the proposed BSRSA strategy, we have set a bound in terms of F_{th} on the number of flows and the size of each flow in which a demand can be split.

In future, new insights on this work could be gained by taking into account the differential delay constraint. The problem can then be converted into RMLSA by integrating it with the distance adaptive modulation so as to minimize differential delay. A more interesting avenue could be to perform defragmentation, and devise rerouting strategies to efficiently utilize the fragments generated during the splitting process.

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