Deterministic lightpath scheduling and routing in elastic optical networks

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Deterministic lightpath scheduling and routing in elastic optical networks

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Abstract

A huge torrent of information being generated from various heterogeneous applications and services is passing to and from the Internet backbone. Accommodating such heterogeneity and preserving the quality of service (QoS) of each traffic profile is a challenging task for operators. The heterogeneous traffic profile (HTP) considered in this work includes permanent lightpath demands (PLDs) and scheduled lightpath demands (SLDs). We propose various distance adaptive routing and spectrum assignment (DA-RSA) heuristics to resolve resource conflict among these two traffic profiles in elastic optical networks (EONs) under a full sharing environment. Conventionally, preemption was the only technique to resolve such conflict and ensure QoS for HTPs. Since excessive preemption leads to poor performance and lowers the degree of customer satisfaction, this work aims at reducing the preemption of demands. In order to do this, we propose to utilize bandwidth splitting as an alternative solution in such situations. Moreover, an integrated solution consisting of splitting and preemption is also proposed. We call this new integration as flow-based preemption. The simulation results demonstrate that utilizing splitting in place of preemption yields significant improvement in terms of all metrics of interest. Moreover, flow-based preemption is proved to be superior in performance than the only splitting-based solution. To the best of our knowledge, this is the first work addressing resource conflicts under a full-sharing environment by focusing on resource utilization at the link and node level. We believe that proposed heuristics support network operators to smoothly orchestrate network resources in the presence of such HTPs.

Keywords

Bandwidth splitting, Elastic optical networks, Quality of service, Routing and spectrum assignment, Scheduled lightpath demands.

1. Introduction

There has been a surge of technological transition in the design and operation of optical networks. The ITU-T flex-grid, orthogonal frequency division multiplexing (OFDM), reconfigurable optical add-drop multiplexers (ROADMs), bandwidth variable transponders (BVTs) are now embraced by optical network operators. All these elements are inherent part of today's optical networks which are known as elastic optical networks (EONs) [1]. Due to the use of flex-grid, the whole optical spectrum is perceived in terms of fine sized blocks which are known as frequency slots (FSs). Unlike traditional optical networks which were based on fixed-grid and wavelength division multiplexing (WDM) technology, the unique feature of EONs is that they are able to allocate just enough bandwidth to the demands by allocating FSs according to the characteristics (such as optical reach, optical path signal to noise ratio, etc.) of the end-to-end optical path. This means EONs are able to transmit optical signals by selecting an appropriate modulation level on the basis of optical reach without the need to regenerate the signal. This distance-adaptive transmission makes EONs highly spectrum efficient and thus this kind of routing and spectrum assignment (RSA) [2] is referred to as distance adaptive RSA (DA-RSA) or routing, modulation level and spectrum assignment (RMLSA) in EONs [3, 4].

EONs receive heterogeneous traffic emerging from various data intensive services (including cloud computing, big data analytics, image processing, etc.) which involve inter-and -intra data center transmissions to and from corporate giants, research organizations, etc. as well as the regular data traffic from domestic users. The inter-and-intra data center traffic involves very huge sized data streams called elephant flows. These elephant flows have very rigid quality of service (QoS) requirements which ensure guaranteed availability of resources. Hence, the request for such traffic flows is made to the network (operator) long before their actual transmission time. Thus, the network operator has a traffic matrix of such connection requests (CRs) ahead of time, indicating their setup time, tear down time and the amount of bandwidth needed. In optical networks, these CRs are known as scheduled lightpath demands (SLDs) [5, 6]. There also exist certain data services which need to be served as and when they arrive and thus they do not have any stringent QoS requirements. The demand for such services is referred to as permanent lightpath demands (PLDs). Unlike SLDs, PLDs do not mention their timing information. PLDs are perceived as greedy in terms of occupying spectral resources; once arrived, they remain in the network as long as the network is functional. Therefore, the traffic matrix of such CRs contains their source-destination (s-d) pair information along with their bandwidth requirement.

The heterogeneous presence of such traffic poses various challenges in front of network operators including: avoiding conflicts in the spectrum assignment where different traffic profiles are sharing the spectrum, accommodating a large volume of bandwidth in the network, meet stringent QoS requirements of data intensive services arriving into the network, achieving greater degree of customer satisfaction, and earning more revenue, etc. Due to all such challenges the scheduling and spectral resource provisioning is of paramount importance to the operators.

In this work, we address the deterministic lightpath scheduling (DLS) problem in EONs in order to resolve the resource conflicts that arise during the resource provisioning for such heterogeneous CRs. DLS, as its name suggests, the problem is deterministic in nature, i.e., it includes the traffic profiles in which the complete traffic matrix is given beforehand. Thus, the DLS problem can be viewed as a variant of static resource planning problem which constitutes a mix of traffic profiles with an aim of increasing the amount of bandwidth accommodated in the network thereby maintaining an efficient utilization of spectral resources. Previous work on provisioning heterogeneous traffic specifically with two traffic profiles in EONs has been presented in [7-13]. However, to the best of our knowledge, the work presented in this paper is the first attempt to solve DLS problem in the context of EONs.

In an environment where spectrum is shared by such heterogeneous CRs, resource competition is very high and hence resource conflict will occur often. This in turn makes the task of spectrum allocation more challenging for the operator. Therefore, allocating spectrum to heterogeneous CRs has become one of the lofty challenges. In such a shared spectrum environment, the provisioning of heterogeneous traffic can be either preemptive (PR) or non-preemptive (NoPR). In PR provisioning, whenever a resource conflict arises in the network, low priority CR(s) relinquish control over the resources and high priority CRs are provisioned on those resources. This is called disruption or preemption of low priority CRs. In contrast to PR, in NoPR provisioning, CRs are served as they arrive.

Preemption is a mechanism to resolve resource conflict in the presence of heterogeneous traffic profiles (HTPs); excessive preemption is hazardous to CRs which are preempted due to resource conflict. Though such preempted CRs are of low-priority, they contribute towards generating revenue and increase overall throughput of the network. Moreover, undue preemption has adverse effects on the network performance such as degraded QoS, poor customer satisfaction and loss of revenue. Hence, whenever PR provisioning is performed, measures have to be taken to minimize such preemptions in the network.

In this work, we have proposed four DA-RSA heuristics for EONs with the objective of accommodating a high volume of bandwidth in the network thereby utilizing spectral resources efficiently. We refer to these heuristics as heterogeneous DA-RSA (HDAR), preemptive HDAR (PHDAR), integrated HDAR with splitting and preemption (IHDAR), split HDAR (SHDAR). The proposed heuristics utilize both NoPR as well as PR provisioning. Initially, SLDs and PLDs are served without performing preemption. Next, we observe the impact of PR provisioning on the network in the presence of SLDs and PLDs. Afterwards, we utilize bandwidth splitting [5] and preemption together to reduce preemption of PLDs. The SLDs are split with respect to their bandwidth in multiple chunks. Simulation results demonstrate superior performance in this case even with the single path routing, which eliminates the need for utilizing complex multi-path routing. To further access the potential of splitting SLDs in alleviating the resource conflicts, we utilized bandwidth splitting instead of preemption of PLDs, in another heuristic. On evaluating the results of these heuristics, it is revealed that when splitting and preemption are used simultaneously, the best performance could be achieved. Thus, through this work it is demonstrated that in EONs splitting could eliminate the need of utilizing preemption in the presence of heterogeneous traffic and in turn avoids the need to disrupt the demands.

The remaining part of this paper is structured as follows: Section 2 reviews the previous work on SLDs, various kinds of static and dynamic HTPs and provisioning of HTPs in EONs. In Section 3, system model and the proposed heuristics are discussed. Section 4 describes the simulation scenario and presents the analysis of results obtained. Finally, Section 5 concludes the paper.

2. Literature review

The concept of SLDs was originally presented by Kuri et al. in [14] with reference to conventional WDM optical networks. In [15] authors categorized PLDs and SLDs as static immediate reservation (IR) and static advance reservation (AR) requests, respectively. The readers are requested to refer [15] to understand more on PLDs and SLDs in detail. The concept of SLDs is relatively new to EONs and it has been discussed in [5, 6]. Authors in [5], utilized the knowledge of spatial and temporal dimension of SLDs to ease the provisioning of voluminous SLDs. They have proposed several RSA strategies in which the bandwidth of SLDs is split into a number of chunks and then routed using either single/multi-path routing. In [6] authors proposed various RSA strategies and addressed the problem of spectrum fragmentation in EONs by considering scheduled traffic and dynamic traffic scenarios separately. In [5, 14] authors did not consider HTPs. Though authors in [6] considered two traffic profiles in their work, they proposed different strategies to serve both the profiles, individually.

In [7] authors proposed a two-dimensional resource model and addressed the issue of spectrum and time fragmentation in EONs. Their proposed algorithm performs DA-RSA for CRs and meanwhile, if any of the AR requests are blocked, the already scheduled ARs (which are not in service) are re-optimized. Authors in [8] classified the spectral resources on the basis of the number of FSs required by CRs to reduce the spectrum fragmentation. The whole spectrum is divided into two prioritized areas: one to accommodate only IRs and other for both IRs and ARs. The border of the prioritized areas is flexible and can be adjusted to control the blocking of AR and IRs. The issue is addressed for multi-fiber EONs. In addition to AR and IR, authors in [9] proposed a weight based RSA heuristic to serve malleable reservation (MR) CRs in EONs. Though they considered a network with such HTPs, they did not observe the effect of these traffic profiles on each other.

In [10] authors proposed various RSA heuristics to reduce spectrum fragmentation and provide a mechanism to control the service level of both IR and AR requests. Instead of OFDM-based EONs authors considered space division multiplexing (SDM) based EON for this study. They have restricted AR requests to use a fixed path routing and allowed IR requests to select the best route among the k-shortest paths available in order to reduce the degradation in IR services. Their proposed strategy does not address the issue of preemption explicitly. In [11] both the proactive and reactive schemes to reduce IR service failures have been presented. In addition to preemption, the IR service failure in their work refers to the blocking of IR services. Authors have tailored the provisioning scheme as per the traffic intensity levels of IR and AR requests. Their proposed reactive scheme allowed reconfiguration of IRs. In EONs, under a dynamic environment, as the CRs come and depart, the issue of spectrum fragmentation arises. Another DA-RSA approach is proposed in [12] wherein authors have utilized splitting, and divided the AR and IR requests in smaller chunks and performed multipath routing to route those chunks. Authors in [13] have utilized preemption while performing QoS aware RSA to reduce the blocking probability of high priority requests. Though their heuristics utilized bandwidth squeezing and fragmentation, and utilized preemption whenever required.

Although there is a very small footprint found in EONs with respect to the provisioning of HTPs, we observed the following: none of the works have considered static HTPs, high priority CRs have been the focus throughout the work and negligence towards the significance of low priority traffic. Hence, degradation of low priority traffic has been there to a great extent. Moreover, the work presented in [9] did not touch upon preemption, and assumed that IRs announce their service duration. This does not happen in a real scenario. The work in [13] has a mention on preemption but the proposal lacks details about how they have selected CRs for preemption and how it has been performed.

The motivation for this work is the result of the fact that low priority requests cannot be ignored at the time of provisioning. The provisioning of HTPs is a real challenge in a shared environment. Preemption of low priority CRs should be performed consciously and it should be kept very low in order to preserve the throughput of the network. In this work, we are focusing on the static HTPs including SLDs and PLDs with the aim to accommodate more bandwidth in the network while reducing the preemption of PLDs in the network. Here, SLDs are considered as primary traffic and thus contrary to the works present in literature, the work assumed that the network traffic is dominated by high priority traffic profiles (i.e., SLDs). Also, conforming to the real scenario, PLDs in this work, are not supposed to announce their service time information. Moreover, to reduce preemption in the network, bandwidth splitting is employed in two ways: first it is informed in PR scenario and later in NoPR scenario. In both the cases, the proposed algorithms perform only single-path routing and save the operator from the complex computations of multi-path routing.

3. Provisioning of heterogeneous traffic profiles (HTPs)

This section describes the nomenclature, constraints and design metrics used in this work. The subsections cover detailed discussion on the proposed heuristics.

A weighted undirected graph $G(N, L, \eta, F)$ is used to describe the physical network topology where, N is the set of nodes, L is the set of bidirectional links adjoining the nodes, weight function $\eta: L \rightarrow \mathbb{R}^+$ which maps the physical length of the links between the nodes in the network and F is the set of FSs on each fiber link $l \epsilon L$. A set of CRs R, where, each CR is denoted as R_i, such that $(i = 1,2,3, \dots, |R|)$ is designed by a tuple $R_i = (s_i, d_i, B_i, \alpha_i, \beta_i)$, where s_i and d_i represent the source and destination nodes of CR, R_i, such that $(s_i, d_i) \epsilon N$; B_i denotes the requested bandwidth (in Gbps), α_i and β_i indicates the setup and tear down times of R_i such that $\beta_i \geq \alpha_i$ if R_i is a SLD. If it is a PLD then α_i denotes the arrival time, and in this case, the value of β_i becomes insignificant as the PLD does not mention its tear down time. We assume that the time is slotted and the duration for each time slot is set to one hour. A set T is used to indicate the set of time slots such that $|T| = 24$. Thus, in simulations, to differentiate between SLDs and PLDs, we set $\beta_i > 24$. In this work, we use k-shortest path routing algorithm with $k = 3$. The set of candidate paths corresponding to R_i is denoted by a set K. These k-candidate paths are pre-computed corresponding to each CR present in set R.

Since EON is equipped with (S)BVTs, we use the set BV to represent the transponders on a node. The capacity of a transponder $b \in BV$ is denoted by $TCap_b$ (in Gbps) and $TCUtil_b$ indicates the utilized capacity of a transponder (in Gbps) $b \in BV$. A variable TSP_n represents the number of (S)BVTs present on $n \in N$. We assume that SBVT is logically divided into a number of sub-transponders (S-TSPs) and each S-TSP is assumed to be a low-capacity BVT. The variable S is used to represent the number of S-TSPs that belong to an SBVT which is bounded by the value of $TCap_b$. That is, the number of S-TSPs belonging to an SBVT should not exceed the total capacity of a SBVT. For this work we assumed it to be $1 \leq S \leq 4$ [5]. If $b \in BV$ is a BVT then $S = 1$. If $b \in BV$ is an SBVT then $TCap_{bn}$ indicates the total capacity of a transponder on node $n \in N$. If the (S)BVT $b \in BV$ is utilized on node $n \in N$, the value of boolean variable $NTSP_{nb}$ is set to 1, otherwise 0. In a non-grooming environment, a BVT can be utilized by only one CR at a time instant; therefore, if $NTSP_{nb} = 1$ for a BVT $b \in BV$ then $TCUtil_b = TCap_b$. The total capacity of transponders utilized on a node is given by,

$$TCap_n = \sum_n^{|N|} \sum_b^{|BV|} NTSP_{nb} \tag{1}$$

The proposed PHDAR and IHDAR heuristics perform preemptive provisioning thereby allowing preemption of PLDs. Thus, the boolean variable keeps track of such preempted PLDs by setting the value of Req_{ip} to 1, otherwise 0. The variable DB_i indicates the amount of bandwidth preempted (i.e., dropped) by the time R_i arrives in the network. If a CR R_i is accepted then the value of variable A_i is set to 1, else 0. In SHDAR and IHDAR heuristics, bandwidth splitting of

SLDs is performed and the flows belonging to a SLD are allowed to route by using single-path routing only. In order to perform splitting, these two heuristics modified the splitting model that we designed in [5]. Contrary to [5], in this work we performed DA-RSA for HTPs and did not perform multi-path routing. Due to this, the mathematical formulations have been revised. We consider four modulation formats (i.e., BPSK, QPSK, 8-QAM and 16-QAM). The values of spectrum efficiency (SE) corresponding to BPSK, QPSK, 8-QAM and 16-QAM are 1, 2, 3 and 4 bits/s/Hz, respectively.

The following constraints should hold:

(i) Since the heuristics are performing DA-RSA, spectrum continuity and contiguity constraints should hold.

(ii) A FS on a link cannot be allocated to either a SLD or a PLD simultaneously, or two SLDs at a time instant. This means, they are not allowed to use a single spectral resource during a time slot. This implies that a PLD can utilize a FS with SLD, only if its arrival time (α) is greater than the tear down time (β) of a SLD, whereas the same FS can be allocated to two SLDs if both of them are disjoint in time. This is known as time-disjointness property of SLDs [5].

(iii) A CR is allowed to be preempted only if it is a PLD. Moreover, a PLD cannot be preempted by other PLD. That means, only SLDs are allowed to preempt PLDs if they could not be allocated their desired number of FSs on a route.

3.1 Heterogeneous distance adaptive routing and spectrum assignment (HDAR) heuristic

We introduced HDAR heuristic in order to perform DA-RSA for the heterogeneous traffic profiles (i.e., SLDs and PLDs) in EONs. HDAR performs NoPR provisioning of SLDs and PLDs within a full-sharing framework. A traffic matrix in the form of set R is given, which is a mix of SLDs and PLDs. These CRs are entering into the network as a tuple mentioned earlier in this section. As a CR enters into the network, HDAR first checks the value of tear down time, β to know whether it is a PLD or SLD. If $\beta > 24$, then CR is identified as PLD, else SLD. Next, it selects the route from available k-candidate paths. Now, according to length of the route, HDAR selects appropriate modulation levels and converts the bandwidth into FSs. This is done in accordance to the value of SE corresponding to the modulation format as follows:

$$RFS_i = \lceil B_i/(SE_i \cdot Slot_w \cdot 2\rceil + GB \tag{2}$$

where, RFS_i, $Slot_w$ and GB indicate the number of requested FSs, width of a FSs (in GHz) and the number of guard bands required, respectively. Next, the desired number of FSs (i.e., RFS) are searched for this CR.

HDAR provisions PLDs as they arrive, and schedules SLDs in the network so that they use network resources during their respective setup times. The route, modulation format and the spectrum, all are assigned to a CR only if it satisfies all the constraints mentioned earlier in this section.

3.2 Preemptive heterogeneous distance adaptive routing and spectrum assignment (PHDAR) heuristic

Unlike HDAR, PHDAR performs PR provisioning of HTPs in this work. At the time of serving PLDs, PHDAR performs similar to HDAR. However, when a SLD arrives, the heuristic starts collecting information about PLDs that are coming across this SLD at the time of performing DA-RSA. If the SLD could not find resources on a route, then all the collected PLDs now become a set of candidate PLDs to be preempted, for this SLD. That is, by preempting one or more PLDs from this set of candidate PLDs, the SLD could be served. In order to select the candidate PLD from among the set, PHDAR first sorts all the PLDs in the set in ascending order of the number of FSs allocated to them. Next, PHDAR sequentially selects a PLD from this sorted list and preempt it by de-allocating the resources occupied by this PLD and again perform DA-RSA for this SLD considering the recently de-allocated resources. Now, if RSA is not successful then PHDAR selects next PLD from the list and repeat the process until the SLD could be accepted in the network.

3.3 Integrated heterogeneous distance adaptive routing and spectrum assignment with splitting and preemption (IHDAR) heuristic

Preemption of PLDs has an adverse impact on the revenue and customer satisfaction from the operator's point of view. In addition to this, the use of SBVTs in EONs has increased its potential to meet diverse QoS requirements of the customers. Therefore, here we propose to utilize bandwidth splitting and preemption in a single heuristic for the first time in EON to reduce preemption of PLDs. Whenever a route with desired number of FSs is not found for a SLD, before preempting any PLD, IHDAR first attempts to serve such SLD by splitting its bandwidth into multiple chunks, referred to as flows; and then considers each flow as an independent SLD. Next, IHDAR performs DA-RSA for each flow. Similar to PHDAR, at this level, IHDAR starts collecting the information about PLDs and maintains a set of candidate PLDs corresponding to each flow. Now, if any of the flow is not able to avail the resources then IHDAR performs preemption of PLDs in a manner similar to PHDAR. Thus, the IHDAR performs splitting at flow level thereby reducing the number of preemptions caused due to SLDs in the network.

IHDAR has a tuning parameter ω which is used at the time of computing flow threshold F_{th}. Here the flow threshold is computed as follows:

$$F_{th} = \lfloor \overline{RB}/\omega \rfloor \tag{3}$$

where, $\overline{RB}$ denotes the mean bandwidth requested by all CRs. Here ω may take values such that $1 \leq \omega \leq 4$. On the basis of this F_{th}, the IHDAR decides that in how many flows a SLD can be split. The variable $NFlow_i$ is used to indicate the number of flows in which a SLD R_i is split. A SLD cannot split into more than S flows i.e., ($NFlow_i \leq S$). Thus, F_{th} balances the value of $NFlow_i$ by tuning the value of ω. $NFlow_i$ is computed as follows:

$$NFlow_i = \lceil B_i / F_{th} \rceil \tag{4}$$

The size of each flow is represented by a variable $SFlow_{i,j}$ is defined as

$$SFlow_{i,j} = \begin{cases} F_{th}, & j < NFlow_i \\ (B_i - (F_{th}.(NFlow_i - 1))), & \text{otherwise} \end{cases} \tag{5}$$

The algorithm for IHDAR is presented in Table 1. It shows how IHDAR performs flow-based preemption.

3.4 Split heterogeneous distance adaptive routing and spectrum assignment (SHDAR) heuristic

In order to see the effect of splitting on HTPs, we propose a NoPR version of IHDAR in the form of SHDAR. Thus, SHDAR employs only splitting with the aim of improving network performance in the presence of HTPs. It performs splitting of SLDs only whenever DA-RSA is unsuccessful on a particular route for a SLD. Here, the splitting process is similar to that of IHDAR. This means, multiple chunks belonging to a SLD are routed using single-path routing. This allowed us to see the benefits that the splitting process has brought to the network.

4. Performance evaluation

This section presents the simulation assumptions and discusses the results obtained from simulations to evaluate the performance of proposed heuristics.

4.1 Simulation assumptions

We evaluate the proposed algorithms by performing simulations in MATLAB using NSFNET as shown in Fig. 1. We assume an EON with 4 THz spectrum in which the spectral width of each FS is 12.5 GHz. Thus, there are 320 FSs in the spectrum. We assume each node in the network is equipped with infinite (S)BVTs, each of which is capable to support the data rates up to 400 Gbps. Each SBVT is further divided into 4 S-TSPs. The line rates required by CRs are assumed to be 25 Gbps, 75 Gbps, 125 Gbps, 150 Gbps, 200 Gbps and 250 Gbps and are uniformly distributed among all CRs in the set R. The transmission distance corresponding to the four modulation formats are 9600 km, 4800 km, 2400 km and 1200 km for BPSK, QPSK, 8QAM and 16QAM, respectively [16]. First-fit spectrum allocation technique is used under a fully shared spectrum in all the proposed heuristics. The HTP is a mix of SLDs and PLDs which are considered in the ratio of 6:4 for the purpose of performance evaluation as we assumed that due to the rise of bandwidth intensive rigid QoS services, there will be more number of SLDs than PLDs in the network. The setup and tear down times for SLDs and the arrival time for PLDs are generated randomly along with the specific line rates required by them. The CRs present in set R are varied at each simulation run and the results presented in the following sub-section are averaged over 10 simulation runs.

4.2 Results and discussion

Since this is the first work concerning static HTPs (i.e., PLDs and SLDs), we consider HDAR as the benchmark to evaluate the performance of the proposed heuristics. HDAR does not employ any spectral resource conflict mechanism and thus becomes a suitable candidate as a benchmark to evaluate the benefits achieved by the proposed conflict resolution heuristics. In case of SHDAR and IHDAR, we have performed simulations for three different values (i.e., 1, 2 and 4) of ω. This value is the crucial factor in deciding the F_{th} as indicated in Table 1. The results reported in this section are with $\omega = 4$. Figure 2 indicates the amount of bandwidth accepted (in Tbps) corresponding to all the heuristics. At low load (i.e., <800 CRs), performance of all the strategies is same. However, as load increases, the gap between HDAR and other proposed heuristics grows significantly. The most and least gain achieved by the proposed heuristics are 26.72% and 10.78% in case of IHDAR and PHDAR, respectively for the metric under consideration. All the heuristics except HDAR employed resource conflict mechanism(s). This highlights the importance of resolving the resource conflict when there are HTPs present in the network. IHDAR and SHDAR accepted 14.38% and 7.84% more bandwidth in the network than PHDAR. This is because whenever a SLD is getting blocked in PHDAR, it preempted more number of PLDs, indicating the inefficiency of PHDAR in utilizing preemption efficiently. Excessive preemption leads to generate more number of fragments when the arriving SLD is not utilizing all the FSs emptied by the candidate PLD(s). IHDAR accepted maximum bandwidth because it achieved a good balance between splitting and preemption by performing flow-based preemption.

The graph shown in Fig. 3 illustrates the link utilization ratio (LUR). This is defined as the ratio of the number of FSs consumed to the number of CRs accepted in the network. The low value on this metric entails good utilization of spectral resources. IHDAR and SHDAR, both have performed identically and the best in terms of LUR. The percentage decrease in LUR between HDAR and PHDAR is 24.19% which is further decreased to 15.09% when the network is heavily loaded. The rate of LUR decrease is highest in HDAR and lowest in case of IHDAR and SHDAR. This is because HDAR does not differentiate among the two traffic profiles, and this resulted in consuming more FSs even for accepting fewer CRs in contrast to IHDAR and SHDAR.

Figure 4 depicts the node utilization ratio (NUR) versus the number of CRs arriving into the network. The NUR which represents ratio of the total (S)BVTs utilized to the amount of bandwidth accepted in the network. At high load, PHDAR achieved nearly same performance as IHDAR and SHDAR. This is because as the CRs increase in the network, (S)BVTs are exhausted. Therefore, only SLDs are accepted because they can utilize the same SBVTs if the time-disjointness constraint is satisfied.

The graph shown in Fig. 5 represents the total number of transponders (TSPs i.e., (S)BVTs) utilized as the CRs arrive in the network. The rate of growth of this curve indicates the amount of CRs accommodated in the network. HDAR has utilized maximum number of TSPs even when the network is lightly loaded whereas in case of IHDAR and SHDAR, the TSPs present in the network are exhausted when the network is heavily loaded. However, PHDAR utilized maximum number of TSPs at a relatively moderate traffic load. At peak load all of the strategies have utilized maximum TSPs available in the network.

The two of the proposed heuristics (i.e., PHDAR and IHDAR) have utilized preemption as the resource conflict resolution technique. The graph presented in Fig. 6 depicts the amount of bandwidth dropped due to preemption of PLDs in both the heuristics. Till about 810 CRs, both the heuristics did not need to utilize preemption to accommodate SLDs in the network. As the number of CRs grew from this point, PHDAR started preempting PLDs which resulted in an increase in the amount of bandwidth dropped in the network. Although IHDAR also preempted PLDs but the rate at which the bandwidth is dropped is very low; thus, it has dropped 13.32% less bandwidth than PHDAR. This is due to the fact that PHDAR employed preemption excessively by dropping more number of PLDs to accommodate every SLD. However, utilizing splitting and preemption together to perform flow-based preemption saves on excessive preemption and hence it drops very small amount of bandwidth.

It is evident from the graphs shown in Fig. 2 - 5 that IHDAR and SHDAR both have outperformed HDAR and PHDAR. Table 2 reaffirms this fact again with respect to the number of FSs utilized and the number of spectral fragments generated in the process of DA-RSA by all the heuristics. The reason for the two heuristics (IHDAR and SHDAR) to have similar performance is again highlighted in the table. Both the heuristics have a minute gap in terms of number of CRs accepted. Although the number of FSs utilized by SHDAR is more, it has generated less number of fragments in the spectrum as compared to IHDAR.

From the simulation experiments it is clear that resolving resource conflicts when there are HTPs in the network, is essential to achieve good performance from the network. Amongst all the heuristics, PHDAR, IHDAR and SHDAR employed either preemption, splitting or both as the conflict resolution technique(s), the results reveal that both IHDAR and SHDAR outperformed

PHDAR. This affirms that only utilizing conflict resolution technique is not enough; a heuristic must utilize them intelligently in order to avoid the adverse effects caused by excessive preemption and splitting.

5. Conclusion

In this paper, various DA-RSA heuristics are proposed in order to perform deterministic lightpath routing and scheduling of HTPs. Conventionally, preemption was the only technique which was used in the full sharing environment to resolve the resource conflict among various traffic profiles. In this work, we proposed to utilize splitting, and splitting with preemption for this purpose under a full sharing framework in EONs. The proposed heuristics employing splitting have demonstrated superior performance by routing all the flows pertaining to a CR via single-path only. Thus, IHDAR and SHDAR are free from the complexities that are otherwise involved when multi-path routing is used. Excessive preemption lowers the throughput and degrades customer satisfaction. Therefore, in this work, we have utilized splitting as a tool to avoid the preemption of PLDs. Simulation results points out that though the number of fragments generated are more in flow-based preemption in IHDAR; it outperformed on all the other metrics of interest and thus is more effective than the heuristics where splitting or preemption has been used in isolation. Though the splitting based heuristics have performed well with single-path routing; in future the effect of performing multi-path routing could be studied on the HTPs.

Declarations

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Conflicts of interest/Competing interest

Not applicable.

Availability of data and material

Not applicable.

Code Availability

Not applicable.

Authors' contributions

People with whom author discussed the work for comments, feedback and suggestions are mentioned in the Acknowledgements Section of the manuscript.

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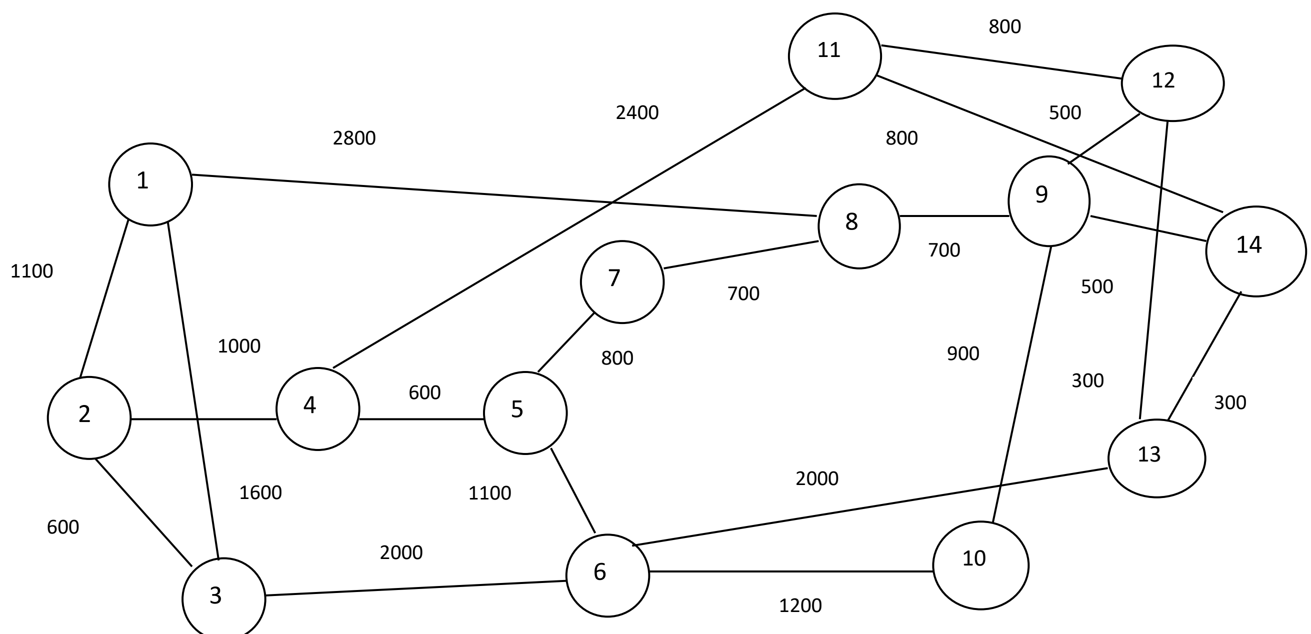

Fig. 1: NSFNET network.

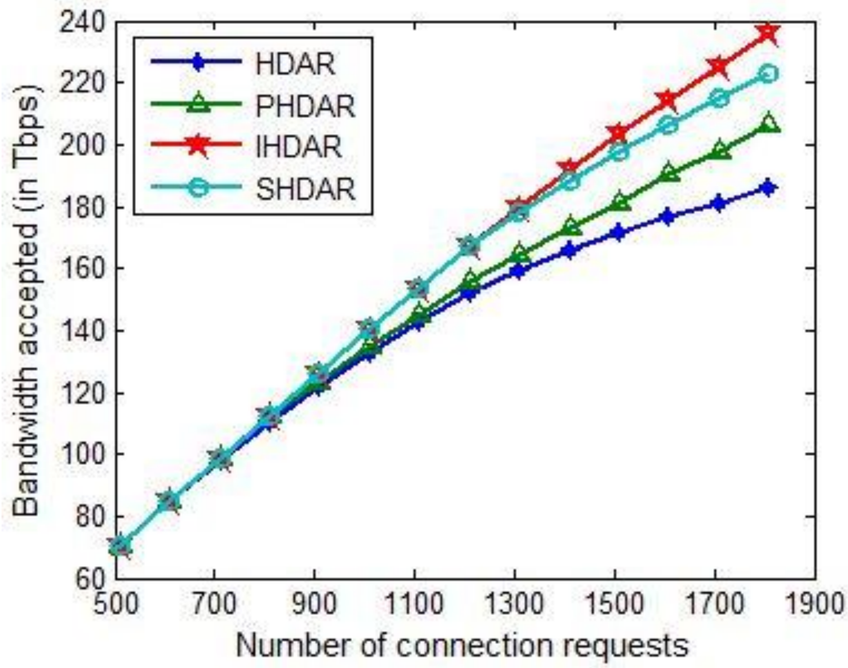

Fig. 2: The amount of bandwidth accepted (in Tbps) with respect to the number of connection requests arrived in the network.

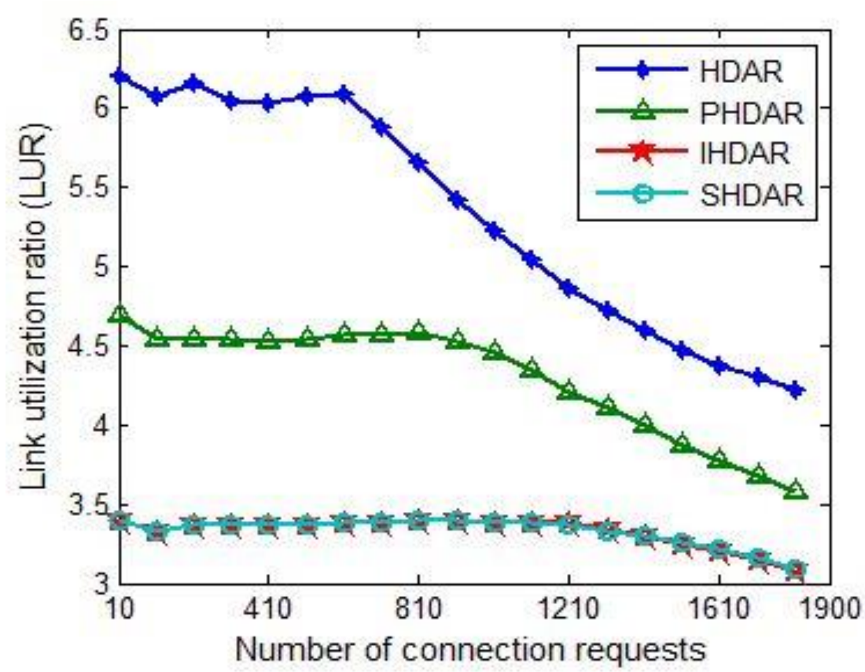

Fig. 3: Link utilization ratio (LUR) with respect to number of connection requests arrived in the network.

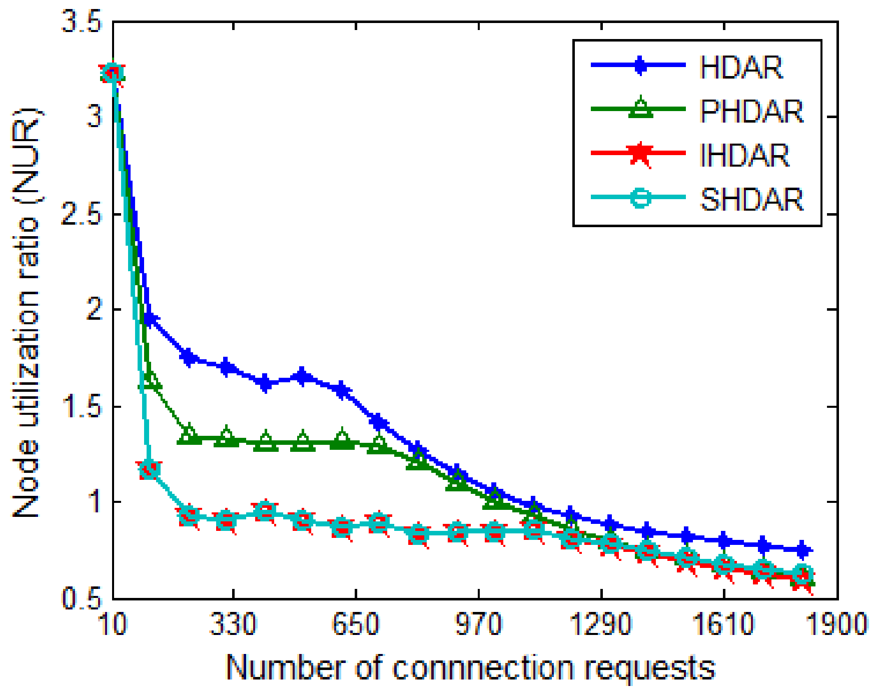

Fig. 4: Node utilization ratio (NUR) with respect to the number of connection requests arrived in the network.

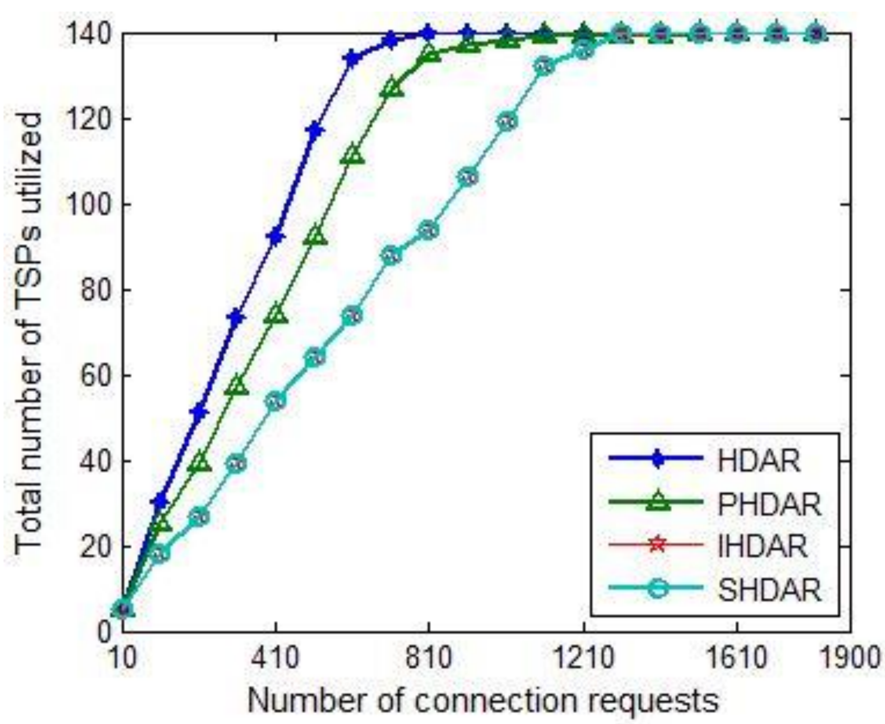

Fig. 5: Number of transponders (TSPs) utilized under each heuristic with respect to the number of connections requests arrived in the network.

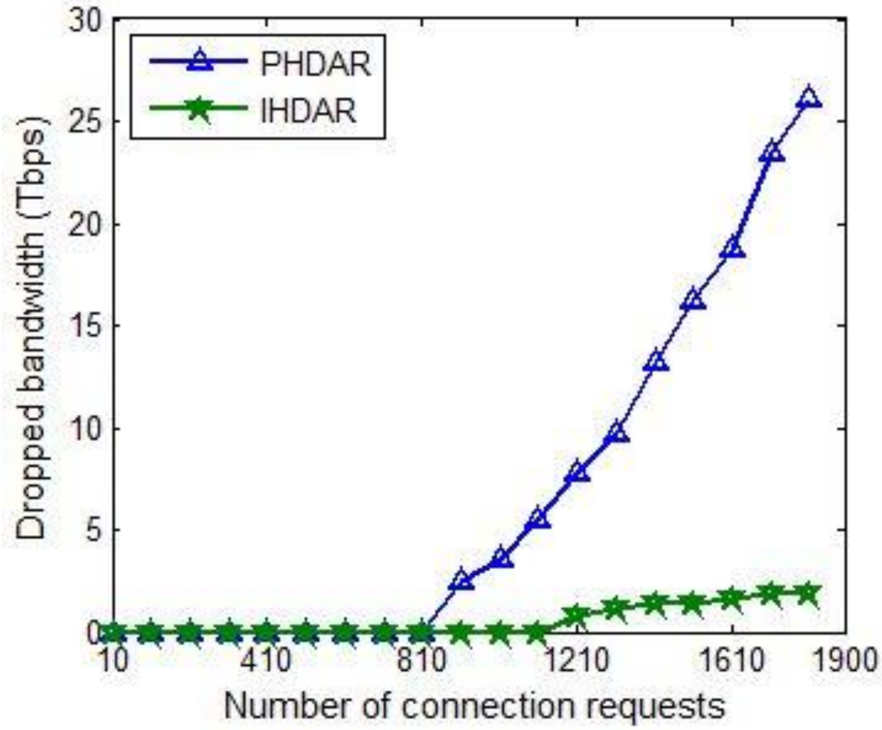

Fig. 6: The amount of bandwidth dropped (in Tbps) with respect to the number of connection requests arrived in the network.

Table 1: Algorithm for IHDAR

Input: Graph $G(N, L, \eta, F)$ representing EON, a set of demands $R(s, d, B, \alpha, \beta)$, a set of pre-computed candidate paths K, transponder capacity $TCap$, $\overline{RB}$.

Output: Route, modulation level and FSs assigned to all requests accepted in the network.

1. **for** all $r_i(\epsilon R)$ **do**
2. **for** all the candidate paths $k_{sd}(\epsilon K)$ **do**
3. $RFS_i = \lceil B_i/(SE_i \cdot Slot_w \cdot 2\rceil + GB$
4. **if** r_i is PLD **then**
5. Perform DA-RSA for PLD by enforcing continuity and contiguity constraints
6. **else**
7. Perform DA-RSA for SLD by enforcing continuity, contiguity and time-disjointness constraints
8. **if** DA-RSA is not successful **then** //perform splitting
9. $F_{th} = \lfloor \overline{RB}/\omega \rfloor$
10. $NFlow_i = \lceil B_i/Flow_{th} \rceil$
11. **for** $j \leftarrow 1$ to$NFlow_i$ **do**
12. **if** $j < NFlow_i$ **then**
13. $SFlow(j) \leftarrow F_{th}$
14. **else**
15. $SFlow(j) \leftarrow B_i - F_{th}.(NFlow_i - 1)$
16. **end if**
17. Perform DA-RSA for SLD r_i using single-path routing
18. **if** DA-RSA is not successful for j **then**
19. **if** size(PLD_DB)>1 **then**
20. Sort all PLDs of PLD_DB in ascending order of FSs assigned to them
21. **end if**
22. **for** all $p_l(\in PLD\_DB)$ **do**
23. Collect the allocated resources' information for p_l
24. De-allocate the resources allocated to p_l
25. Perform DA-RSA for SLD on this (already selected) route
26. **if** DA-RSA is successful for j **then**
27. **break;**
28. **end if**
29. **end for**
30. **end if** // line 18
31. **end for**
32. **end if** // line 8
33. **end if** // line 4
34. **if** DA-RSA is successful on this route **then**
35. Update link status
36. Update SBVT capacity and the number of available S-TSPs
37. $A_i \leftarrow 1$
38. **break**;
39. **else**
40. **if** $k_{sd}(\epsilon K) = \emptyset$
41. $A_i \leftarrow 0$

```
      end if
    end if
  end for
end for
```

Table 2

The values obtained by proposed heuristics on different parameters

S. No.	Heuristic	Requests accepted	FS utilized	Fragments generated
1.	HDAR	1375	5792	917
2.	PHDAR	1673	5474	1339
3.	SHDAR	1735	5358	1226
4.	IHDAR	1737	5304	1246