Optical Fiber Technology 30 (2016) 167–175

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

A Multi-Backup Path Protection scheme for survivability in Elastic Optical Networks

Dharmendra Singh Yadav *, Abhishek Chakraborty, B.S. Manoj

Department of Avionics, Indian Institute of Space Science and Technology, Thiruvananthapuram 695547, India

ARTICLE INFO

Article history:
Received 5 November 2015
Revised 23 March 2016
Accepted 7 May 2016
Available online 13 May 2016

Keywords:
Multipath routing
Protection/restoration
BSR-MPP
SLICE
Frequency slot
Routing
Modulation-level and spectrum assignment
Bandwidth Blocking Probability

ABSTRACT

Two important challenges in designing a survivable optical network are minimizing backup spectrum allocation and ensuring spectrum assignment constraints. Allocating backup spectrum is one important approach for survivable optical network design. Connection requests which are rejected due to the unavailability of a single backup path can be survived using multiple backup routes. Multiple backup routes not only increase connection acceptance rate, but also improve backup resource sharing. In this paper, we present a strategy for survivability which optimizes primary and backup spectrum allocations and multiple backup route assignments for surviving a connection request. In our strategy, named as Backup Spectrum Reservation with MultiPath Protection (BSR-MPP), multiple backup routes are searched over advance reserved backup resources when an optical connection is concerned. Simulation results show that confinement of backup resources result in higher resource sharing and assignment of multiple backup lightpaths. It can also be observed that BSR-MPP has lower Bandwidth Blocking Probability and higher spectrum efficiency as compared to conventional Shared Path Protection (SPP) and MultiPath Protection (MPP) strategies.

1. Introduction

Advancement of the optical network technology from the rigid Wavelength Division Multiplexing (WDM) to the flexible spectrum allocation has paved the way for higher utilization of the optical fiber bandwidth. In an optical network, bandwidth demand may vary from a few Gbps to hundreds of Gbps [1]. Spectrum sliced elastic optical path network (SLICE) architecture [1] leads to spectrum efficiency by incorporating unused spectrum, taking from sub-channel to super-channel, which is not employed in conventional WDM architectures. A network based on SLICE architecture is also known as flexible optical network or Elastic Optical Network (EON).

In EON, a network node has the ability to assign wide range of bandwidth when user data demand arrives from the upper client layers. Connection request provisioning in an EON is based on the Routing, Modulation, and Spectrum Assignment (RMSA) [2,3] approach. In RMSA, spectrum requirement is computed based on the length of an optical route. For shorter route, higher level of Modulation Format (MF) is used in order to ensure lower usage of spectrum. EON architecture is mainly based on Sliceable Bandwidth Variable Transponder (SBVT) and Bandwidth Variable cross Connect (BV-WXC).

SBVT can generate signals of variable spectrum demand based on transmission distance. SBVT consists of laser sources, electronic processing domain, and Photonic Integrated Circuit (PIC). Laser sources generate signals based on bandwidth demand, whereas electronic processing domain filters optical signals. PIC, on the other hand, helps in switching optical signals to the optical multiplexer. Different types of MFs can be used by the laser sources for transmission of optical signals. Modulation formats can be Binary Phase Shift Keying (BPSK), Quadrature Phase-Shift Keying (QPSK), 8-Quadrature Amplitude Modulation (8-QAM), or 16-Quadrature Amplitude Modulation (16-QAM) in EONs. Lower MF supports higher distance of transmission by compromising spectrum efficiency. A detailed architecture of SBVT can be found in [4–6].

The implementation of BV-WXC, used for cross connection of input signals to output signals, is relied on Bandwidth Variable Spectrum Selective Switches (BV-SSSs) that function like add-drop of signals based on optical routes/lightpaths. BV-SSS is made of Liquid Crystal on Silicon (LCoS) or Micro Electro-Mechanical System (MEMS) [4].

As link failure in an optical network results in data as well as revenue losses, designing a survivable network is of prime importance. Network survivability is the ability to reroute the data of a

* Corresponding author.
E-mail addresses: dsyadav_davv@rediffmail.com (D.S. Yadav), abhishek2003slg@ieee.org (A. Chakraborty), bsmanoj@ieee.org (B.S. Manoj).

http://dx.doi.org/10.1016/j.yofte.2016.05.003
1068-5200/

failed link over an alternate route. Several strategies have been proposed in literature to incorporate survivability in the context of EONs. The survivable strategies can be classified in two types, *protection* and *restoration*. In protection or pre-planned mechanism, alternate routes are reserved in advance before the beginning of a communication. In contrast, restoration is the process of recovering the connection after a failure. In EONs, the issue of survivability becomes more compelling due to the enforcement of spectrum continuity and contiguity constraints.

Spectrum continuity constraint requires assignment of the same numbered Frequency Slots (FSs) on all links of a route while enforcing the selection of consecutive FSs [2]. Both primary and backup routes, in EONs, must satisfy continuity and contiguity constraints for all links of an optical route. Hence, spectrum constraints increase design complexity of survivable EONs than conventional WDM architectures.

In this paper, we present Backup Spectrum Reservation with MultiPath Protection (BSR-MPP) scheme which efficiently utilizes network capacity for backup routes and provides more resources for primary routes. Remaining of this paper is organized as follows. Existing literature related to the survivability in the context of EONs is covered in Section 2. Our proposed BSR-MPP strategy, in Section 3, is then explained. Section 4 describes survivability in EONs and compares the performance of our proposed approach with existing strategies namely Shared Path Protection (SPP) and MultiPath Protection (MPP). Finally, we conclude our paper in Section 5.

2. Related work

There are a few existing literature related to the survivability in EONs. In survivable strategies, backup routes are either pre-planned or post computed after a failure. In pre-planned (protection) strategy, backup resources are reserved in advance of connection establishment. On the other hand, in restoration, backup routes are computed online after a failure solely based on the status of the network. Survivability is addressed in a few literature when EONs are concerned.

In [7], authors presented a comparison between a conventional Shared Backup Path Protection (SBPP) and Dedicated Path Protection (DPP) schemes using Integer Linear Programming (ILP) optimization approach under static traffic scenario. Mixed Integer Linear Programming (MILP) optimization for DPP proposed, in [8], at different levels of backup bandwidth squeezing. Authors of [9] compared an ILP model for SBPP with 1 + 1 protection at different levels of squeezing. In [10], authors proposed a minimum free spectrum block consumption algorithm with a tradeoff between spectrum block and joint failure probability. Elastic Separate Protection At Connection (ESPAC), presented in [11], was based on spectrum assignment (i.e., first-fit for primary and last-fit for backup routes). The ILP model in [12] showed spectrum efficiency of MultiPath Provisioning than traditional SPP with the recovery of partial as well as full bandwidth protections at static traffic scenarios.

In [13,14], the concept of Bandwidth Squeezed Restoration (BSR) was proposed to minimize the bandwidth utilization of a network. The scheme showed spectral efficiency and recovered many connections when failure was concerned, for the best effort and bandwidth guaranteed traffic. In [15], authors proposed After Failure Repair Optimization (AFRO) strategy based on rerouting of existing lightpaths from the highly loaded link to the restored link that resulted in uniform distribution of load and better utilization of the repaired links. A dynamic OpenFlow based lightpath restoration mechanism presented in [16] and its performance tested on the Global Environment for Network Innovations (GENI) testbed. In [17], authors presented a multipath restoration strategy. The advantage of multipath routing based schemes relied on the easiness of availability of small spectrum chunks satisfying spectrum continuity and contiguity constraints. However, survivability achieved at the cost of redundant guard bands and differential delay between various chunks received at the destination. Restoration of multi-link failure recovery based on traffic-aware load balancing discussed in [18]. For concurrent failures of primary and reserved backup routes, a survival traffic cognition algorithm presented in [19].

In the following section we discuss a novel strategy, Backup spectrum Reservation with MultiPath Protection (BSR-MPP), which can efficiently address survivability when an EON is concerned.

3. Backup Spectrum Reservation with MultiPath Protection (BSR-MPP)

In Backup Spectrum Reservation with MultiPath Protection (BSR-MPP), available spectrum is split into two parts, primary spectrum and backup spectrum, which are utilized for connection establishment. When a connection request arrives, a primary route is first searched over the primary spectrum. If a primary route is available, then searching is initiated for the respective backup route which is confined only to the advance reserved spectrum. If the connection request is not survived by a single backup route, then a second backup route is assigned to the request. Reservation of spectrum ensures continuity as well as contiguity of all similar-indexed Frequency Slots (FSs) for all links; hence, sharing of FSs is increased because of the removal of spectrum conflict between primary and backup lightpaths. However, this situation is not obvious when SPP and MPP are concerned. In order to minimize the effect of guard bands, searching of a second backup lightpath comes into consideration only when spectrum is not available on the first backup lightpath. Our BSR-MPP algorithm, where first-fit spectrum assignment strategy is used for primary and backup routes, is presented in Algorithm 1.

Algorithm 1. Backup Spectrum Reservation with MultiPath Protection (BSR-MPP)

```
P_{s,d} : Primary route with source s and destination d
B^j_{s,d} : j^th backup route with source s and destination d
Input: A connection request R(s,d,k) where s, d, and k
    represent the source node, the destination node, and the
    demanded bandwidth (in GHz)
Set Request_Accepted_Flag = 0
BW_p^max ← Maximum available bandwidth (in GHz) for P_{s,d}
if (BW_p^max < k) then
    goto step 18        ▶ Bandwidth is not available for primary route
end if
BW_{B,1}^max ← Maximum available bandwidth (in GHz) for B^1_{s,d}
if (BW_{B,1}^max ⩾ k) then
    Request_Accepted_Flag = 1
    goto step 18        ▶ If the request is survived by single backup route
end if
BW_{B,2}^max ← Maximum available bandwidth (in GHz) for B^2_{s,d}
```

15: **if** $(BW_{B,2}^{max} \geqslant k - BW_{B,1}^{max})$ **then**
16: Request_Accepted_Flag = 1
17: **end if**
18: **if** (Request_Accepted_Flag = = 1) **then**
19: Connection request is accepted
20: **else**
21: Connection request is rejected
22: **end if**

Step 4 represents a flag which becomes 1 if the request is accepted. Step 5 shows primary routes with maximum bandwidth (in GHz) availability. Executions of Steps 6–8 handle rejected connection requests due to the unavailability of spectrum for primary route. Steps 9–13, on the other hand, show that connection is survived by a first backup route. However, if the first backup route does not have sufficient bandwidth, a second backup route is allocated to fulfill the request (Steps 14–17). In cases where the second backup path does not have sufficient bandwidth, the connection request is blocked.

Spectrum availability on primary and backup routes follows spectrum continuity and contiguity constraints. Eq. (1) (see Section 3.2) shows the number of FSs required for the demanded bandwidth. Spectrum requirement for primary and backup routes depends on the length and Modulation Format (MF) used. Usually backup routes are longer than primary routes and thus, backup routes use lower MFs. Therefore, both the routes may require different FSs for the same connection request. In this paper, simulation experiments are carried out by taking two backup lightpaths into account. More than two backup lightpaths are not considered because more backup lightpaths consume more resources due to (i) increase in the path length, (ii) additional bandwidth required, and (iii) increase in spectrum consumption of guard bands.

Table 1
Simulation parameters.

Name of Parameter	Value
Number of frequency slots per link (FS)	300
Bandwidth of a frequency slot (BW_{slot})	12.5 GHz
Capacity of a frequency slot with MF = 1 (C_{slot})	12.5 Gbps
Transmission reach of BPSK (MF = 1)	9600 km
Transmission reach of QPSK (MF = 2)	4800 km
Transmission reach of 8-QAM (MF = 3)	2400 km
Transmission reach of 16-QAM (MF = 4)	1200 km
Range of bandwidth request demand	12.5–200 GHz

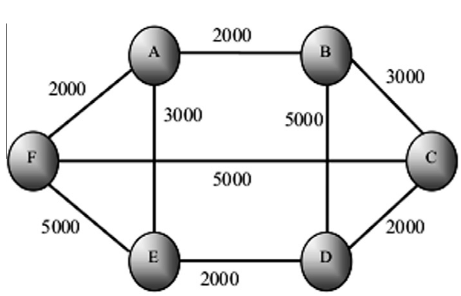

Fig. 1. An example topology to illustrate the working of Shared Path Protection (SPP), MultiPath Protection (MPP), and Backup Spectrum Reservation with Multi-Path Protection (BSR-MPP) strategies. The value of each link in the figure represents the distance between two nodes in kilometers.

3.1. Time complexity analysis of BSR-MPP algorithm

The time complexity of our proposed BSR-MPP algorithm (Algorithm 1) can be estimated as follows. Consider a network of N nodes, L links, and K frequency slots. Let M frequency slots are reserved for the backup route assignment. It is assumed that FS availability can be checked only in $\mathcal{O}(1)$ time. Shortest path (primary/backup) is calculated by applying Dijkstra's algorithm [20] with computational complexity of $\mathcal{O}(N \log N)$. The worst case computational complexity of Step 5, in Algorithm 1, for calculating primary route is $\mathcal{O}(N \log N)$. Similarly, the worst case complexity of Steps 9 and 14 (see Algorithm 1) is also computed in $\mathcal{O}(N \log N)$. Rest of the steps of Algorithm 1 can run only in unit time, i.e. $\mathcal{O}(1)$. Thus, the overall complexity of BSR-MPP algorithm is $\mathcal{O}(N \log N)$.

3.2. Primary and backup routes provisioning using routing, modulation, and spectrum assignment (RMSA)

In this section we formulate the problem of spectrum assignment, based on the path length, for primary and backup lightpaths. Consider a network topology $G(N, L, D, S)$ where N, L, and D represent the sets of nodes, links, and the length of the links, respectively. S in $G(\cdot)$, on the other hand, represents the spectrum availability at each link. Let us assume the bandwidth of an FS (BW_{slot}) is 12.5 GHz [2,3]. Capacity of an FS can be calculated as $MF \times BW_{slot}$ where MF is the modulation format measured in bits per symbol [3]. In this paper, we assume four modulation formats, namely Binary Phase Shift Keying (BPSK), Quadrature Phase-Shift

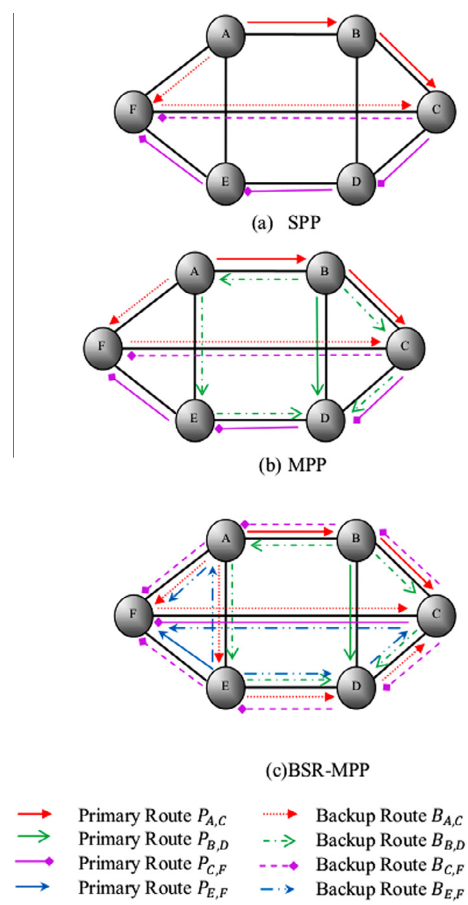

Fig. 2. Primary and backup route assignments in (a) SPP, (b) MPP, and (c) BSR-MPP survivable strategies.

Keying (QPSK), 8-Quadrature Amplitude Modulation (8-QAM), and 16-Quadrature Amplitude Modulation (16-QAM). The values of MFs for BPSK, QPSK, 8-QAM, and 16-QAM are 1, 2, 3, and 4, respectively. Let C_{slot} represents the capacity of an FS when MF is BPSK. Thus, $C_{slot} = MF \times BW_{slot} = 1$ bits per symbol $\times$ 12.5 GHz = 12.5 Gbps. Selection of an MF depends on the length of a route. We have used Table 1 from [3] to identify various values of MFs when different transmission distances are concerned.

For a connection request $R(s, d, k)$ where s and d are the source and destination nodes, and k is the bandwidth demand in GHz, the number of FSs required for a given route can be estimated using the following equation [3].

$$FS = \frac{k}{MF \times C_{slot}} + N_{GB}, \tag{1}$$

where C_{slot} is the capacity of an FS, and N_{GB} is the number of slots used for guard bands. It can be noticed that a route with short distance is assigned higher MF value which results in lower number of FSs [3]. Since backup routes are typically longer than primary routes, backup routes need more FSs.

3.3. An example to illustrate the working of SPP, MPP, and BSR-MPP

To illustrate three strategies, i.e., Shared Path Protection (SPP), MultiPath Protection (MPP), and Backup Spectrum Reservation with MultiPath Protection (BSR-MPP), we consider an optical network with 6 nodes and 9 links as shown in Fig. 1. Each link supports 125 GHz of data where link bandwidth is divided into ten frequency slots each with 12.5 GHz [3]. Let four connection requests, R_1 to R_4, arrive at the network of Fig. 1 as shown in Table 2. Each connection request needs bandwidth of 62.5 GHz. The number of FSs needed for bandwidth demand can be calculated using Eq. (1). The value of C_{slot}, for FS computation, is considered as 12.5 GHz as shown in Table 1. One FS is assigned as the guard band to a connection request. In our example scenario, we consider first-fit strategy for all spectrum assignments.

In SPP, for request R_1, primary route A-B-C and backup route A-F-C are searched (see Fig. 2(a)). Lengths of the primary and backup routes are 5000 km and 7000 km, respectively. As per Table 1, modulation format is BPSK (i.e., MF = 1) as data has to travel a distance longer than 4800 km. Thus FSs needed for primary and backup routes, from Eq. (1), is 6 where one extra FS is allotted as the guard band. Table 2 shows assignment of primary and backup routes for R_1 where FSs {1–5} are allotted as per first-fit spectrum assignment policy. On the other hand, FS 6 is assigned as guard band as shown in Fig. 3. For R_2, link B-D is primary route, hence, it is not available for backup routes B-C and B-A. Therefore, R_2 is rejected due to backup spectrum unavailability. For R_3, C-F (1–6) cannot be assigned as primary lightpath because FSs are already reserved for backup routes of R_1. Therefore, R_3 is survived by following routes: C-D-E-F (1–6) as primary and C-F (1–6) as backup lightpaths, respectively. In case of R_4, backup spectrum is available at E-A-F with the sharing of request by R_1; however, spectrum is not available for primary routes E-F and E-D, respectively.

In MPP, request R_2 is accepted with primary lightpath B-D (1–6) and two backup routes, i.e., B-C-D (7–10) and B-A-E-D (7–9) (see Fig. 2(b)), respectively. The backup bandwidth demand is split into two parts, 4 and 3 with the ease of spectrum availability in the two routes. MPP caters more requests than SPP with an advantage of splitting backup spectrum demand into multiple partial spectra. Moreover, each partial spectrum is assigned with a separate backup route between end nodes. Table 2 shows route assignment of MPP strategy.

Table 2
Primary and backup route assignment for various connection requests in Fig. 2.

Sl. No.	Requests	SPP		MPP			BSR-MPP		
		Primary (FS)	Backup (FS)	Primary (FS)	First backup (FS)	Second backup (FS)	Primary (FS)	First backup (FS)	Second backup (FS)
R_1	A-C	A-B-C (1–6)	A-F-C (1–6)	A-B-C (1–6)	A-F-C (1–6)	*No Need*	A-B-C (5–10)	A-F-C (1–4)	A-E-D-C (1–3)
R_2	B-D	*Rejected*		B-D (1–6)	B-C-D (7–10)	B-A-E-D (7–9)	B-D (5–10)	B-C-D (1–4)	B-A-E-D (1–3)
R_3	C-F	C-D-E-F (1–6)	C-F (1–6)	C-D-E-F (1–6)	C-F (1–6)	*No Need*	C-F (5–10)	C-B-A-F (1–4)	C-D-E-F (1–3)
R_4	E-F	*Rejected*		*Rejected*			E-F (5–10)	E-A-F (1–4)	E-D-C-F (1–3)

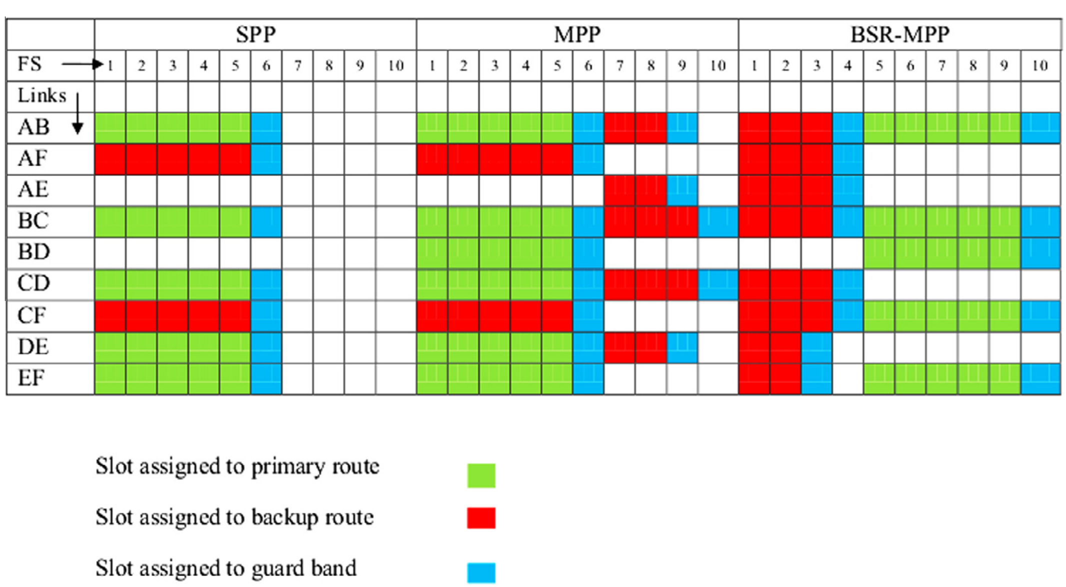

Fig. 3. Spectrum assignments in SPP, MPP, and BSR-MPP survivable strategies.

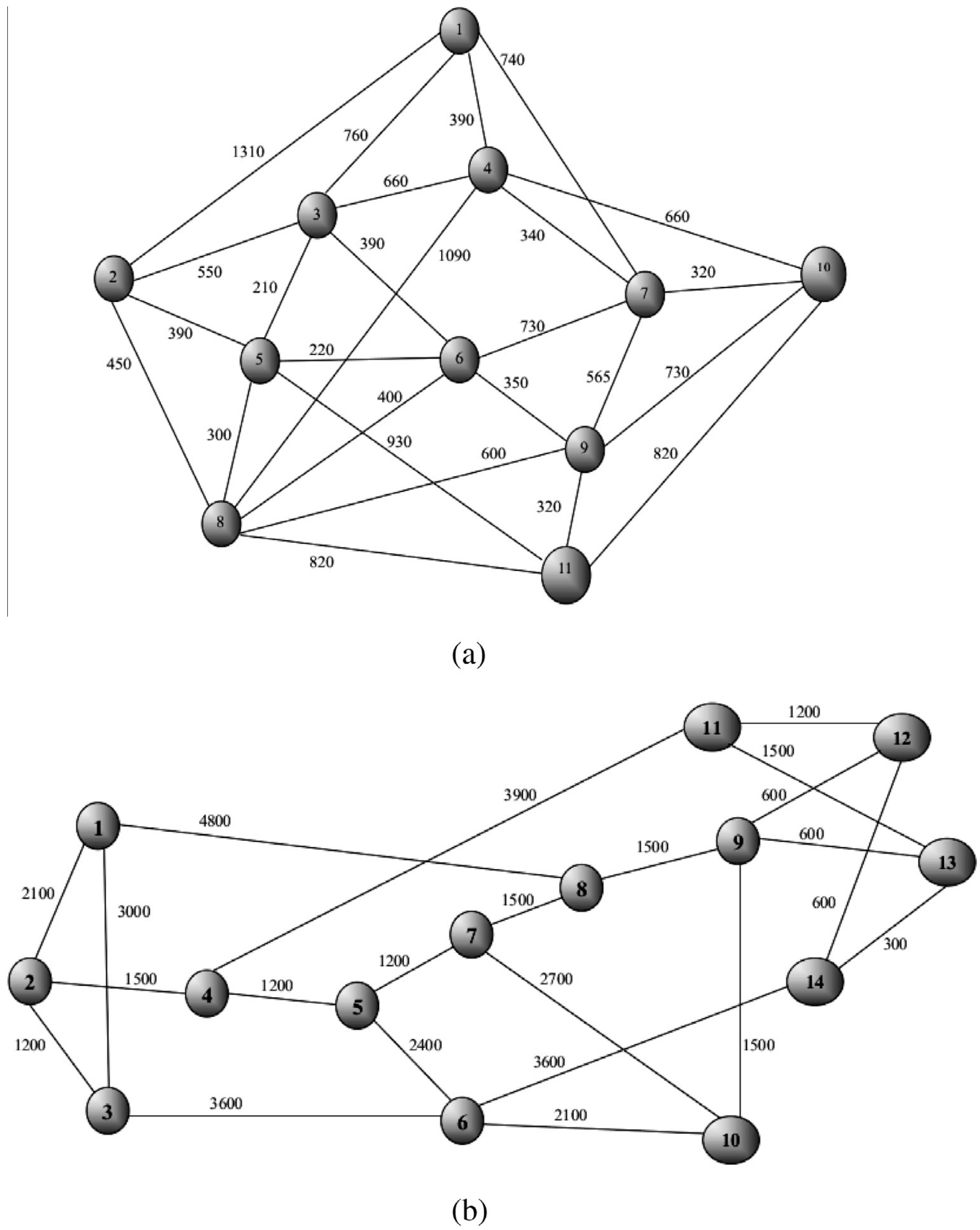

Fig. 4. (a) Cost239 (11 Nodes, 26 Links) topology and (b) NSFNET (14 nodes, 22 Links) topology.

In BSR-MPP, on the other hand, spectrum is split into two parts for the provisioning of primary and backup routes. Let {1–4} frequency slots be assigned for the utilization of backup lightpaths and the remaining slots, i.e., {5–10}, be assigned as primary routes. For R_1, a primary route A-B-C (5–10) with two backup routes, A-F-C (1–4) and A-E-D-C (1–3), are assigned (see Fig. 2(c)). Since four FSs of each link are reserved for backup routes, two backup lightpaths are assigned to primary routes. Similarly, primary and backup routes are assigned to R_2 to R_4 as shown in Fig. 2(c) and Table 2.

Fig. 3 shows FS assignment in the context of different survivable strategies. The figure shows partitioning of spectrum for primary and backup lightpaths that minimizes the effect of route vulnerability due to spectrum continuity, contiguity, and conflict with primary spectrum. Optimized allocation of backup network capacity increases sharing of FSs and assignment of multipath backup routes. Hence, more number of connections can be survived in BSR-MPP as compared to SPP and MPP strategies.

4. Results and discussion

The performance of the survivable schemes in the context of SPP, MPP, and BSR-MPP are evaluated on Cost239 (11 nodes and 26 links) [21] and NSFNET (14 nodes and 22 links) [3] topologies as shown in Fig. 4(a) and (b). We assume that the bandwidth of a link is limited to 3750 GHz, and is divided into 300 Frequency Slots (FSs) where each slot has a width of 12.5 GHz. This is equal to 12.5 Gbps when the Modulation Format (MF) is BPSK (that is, MF = 1) [3]. A connection request $R(s,d,k)$ arrives randomly with unit mean time. The bandwidth capacity demand k varies from 12.5 GHz to 200 GHz. We consider the number of connection requests arriving in unit time is modeled as a Poisson distributed random process with mean arrival rate λ per unit time and the connection holding time is assumed to follow exponentially distributed random process with mean μ seconds. Hence, the traffic load is given as λ/μ in erlang. In all strategies, searching of primary

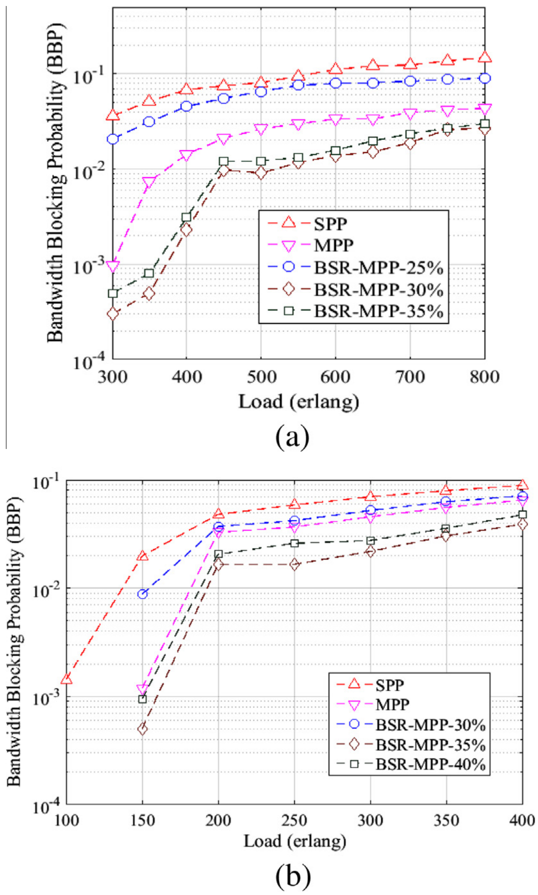

Fig. 5. Bandwidth Blocking Probability (BBP) with the network load in erlang for (a) Cost239 topology and (b) NSFNET topology.

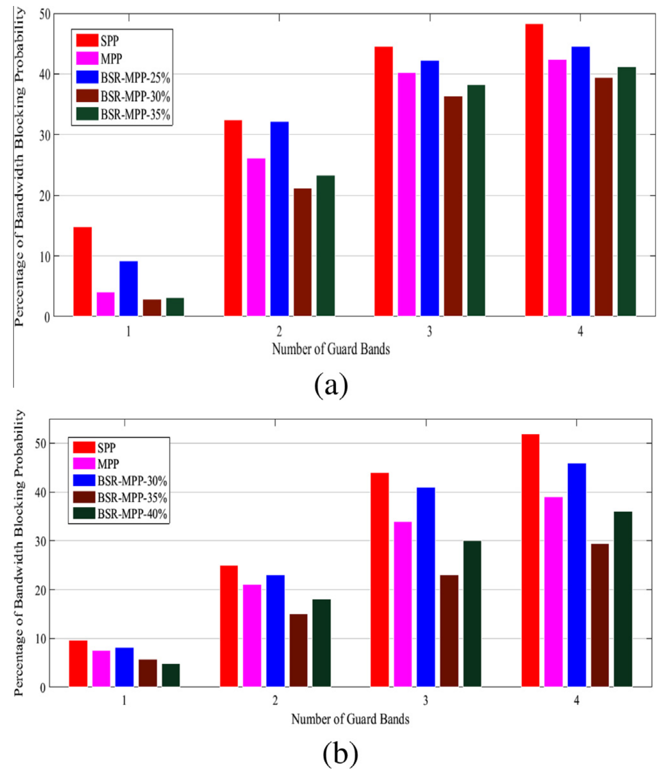

Fig. 6. Bandwidth Blocking Probability (BBP) with the number of the guard bands used for (a) Cost239 topology with network load of 800 erlang, and (b) NSFNET topology with network load of 400 erlang.

and backup lightpaths follow spectrum continuity, contiguity, and non overlapping constraints [10,11], and all spectrum allocations are based on first-fit assignment strategy. MF of each route is decided on the basis of network parameters as given in Table 1. As a result, FSs needed for primary and backup routes may be different. For evaluating performances of SPP, MPP, and BSR-MPP strategies, 10^5 connection requests are generated on a MATLAB based simulator.

We evaluate the performance of BSR-MPP on three primary and backup spectrum allocations in the context of Cost239 and NSFNET topologies. Here 25%, 30%, and 35% backup spectrum allocations for Cost239 topology represent three scenarios namely (i) under-backup allocation where only 25% spectrum of the total available spectrum of a link is used for backup routes, (ii) optimized backup allocation where 30% spectrum of a link is used for backup routes, and (iii) over-backup allocation where an excessive, 35%, spectrum is allocated for backup routes. On a similar note, 30%, 35%, and 40% spectrum allocations are carried out for NSFNET topology. In under-backup resource allocation, sufficient spectrum is not available for backup routes which results in rejection of connection requests. On the other hand, primary routes suffer from the problem of spectrum unavailability when over-backup allocation is concerned. Hence, spectrum partitions should be moderate for balancing resource availability for primary and backup routes. In the optimized backup allocation, availability of primary and backup routes is higher than the under-backup and over-backup allocations. Therefore, performance of the optimized resource allocation of our proposed strategy (i.e., BSR-MPP) is better when Bandwidth Blocking Probability (BBP) is concerned. In NSFNET, average route length of a connection is higher than Cost239 topology and thus, lower MF is used for data transmission. However, lower value of MF represents poor spectral efficiency when network resource allocation is concerned. Hence, it results in different spectrum assignment for primary and backup routes of NSFNET topology than Cost239 topology.

Fig. 5(a) and (b) show BBP performance with respect to network load. BBP is defined as the ratio of the rejected bandwidth to the total bandwidth demanded [11]. From the figures, it can be observed that BSR-MPP has lower BBP as compared to other two strategies (that is, SPP and MPP). In BSR-MPP, backup route availability is higher over the reserved FSs with spectrum continuity and contiguity constraints. We evaluate three backup assignment scenarios in the context of spectrum reservation. Out of three scenarios of BSR-MPP, 25% (30% for NSFNET topology) and 35% (40% for NSFNET topology) for Cost239 topology, respectively, represent under-backup and over-backup spectrum allocations, while 30% (35% for NSFNET topology) shows the optimized backup resource assignment. The optimized reservation of BSR-MPP experiences minimum BBP than the other two cases. In under-backup allocation, connections are rejected due to lack of backup spectrum availability (i.e., under-provisioning) which results in higher BBP. On the contrary, in case of over-backup allocation, rejection due to less spectrum space availability (i.e. 65% for Cost239 and 60% for NSFNET topologies) is observed for primary lightpath assignments. Therefore, connections get rejected due to spectrum unavailability in primary routes (steps 6–8 of Algorithm 1) than the optimized 30% (35% for NSFNET topology) allocation in Cost239 topology. However, BBP is still lower than SPP and MPP strategies.

To analyze the effects of guard bands on the performance of the before mentioned strategies (i.e., SPP, MPP, and BSR-MPP), we simulate the two topologies with fixed network load (800 erlang for Cost239 topology and 400 erlang for NSFNET topology) and different values of guard bands. The bar graphs of Fig. 6(a) and (b) show

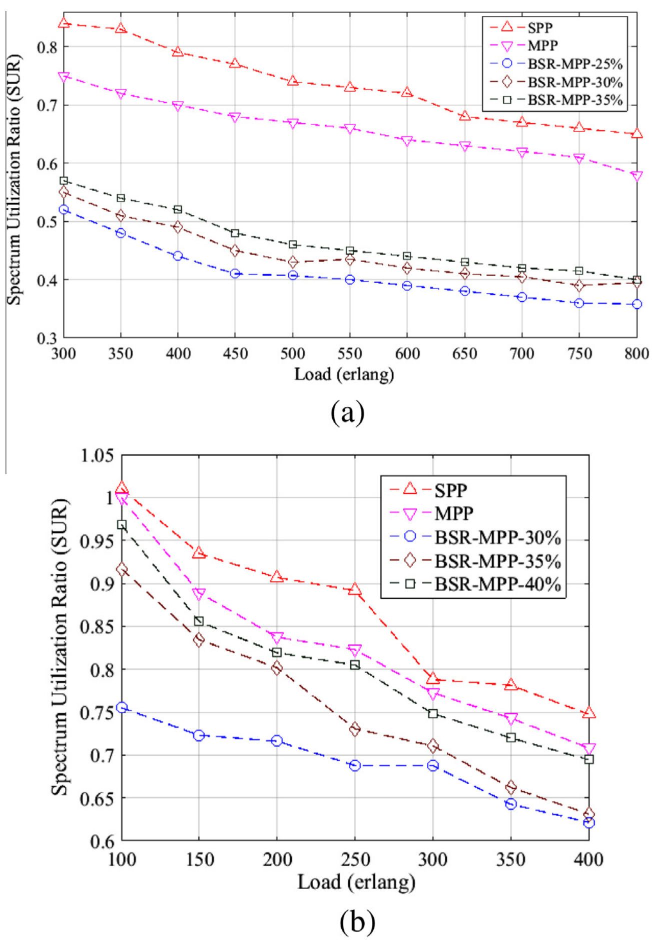

Fig. 7. Variation in Spectrum Utilization Ratio (SUR) of (a) Cost239 topology and (b) NSFNET topology.

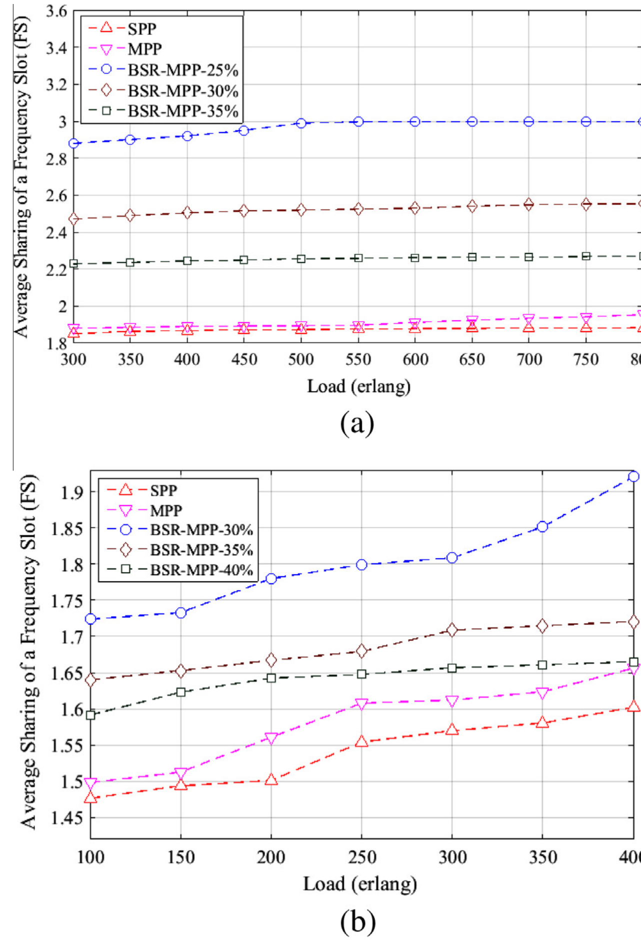

Fig. 8. Average sharing of a Frequency Slot (FS) of (a) Cost239 topology and (b) NSFNET topology.

the percentage variations of BBP with guard bands. The figures show that BBP drastically increases when the numbers of guard bands are increased. Increase in the value of BBP is due to the allocation of more resources to the redundant guard bands which are introduced in the network with addition of each new route. Therefore, in MPP and BSR-MPP, multiple backup routes are assigned only when a single route is unavailable. Sharing of backup resources in BSR-MPP (see Fig. 8(a) and (b)) minimizes the effect of guard bands on backup route assignment. For primary connections, resource sharing is prohibited, and thus, the effect of guard bands is same for all three strategies.

Fig. 7(a) and (b) show the behavior of Spectrum Utilization Ratio (SUR) with network load. SUR is defined as the ratio of the utilization of backup resources to primary resources [18]. Hence, higher SUR represents more resources assigned to backup lightpaths. At low network load, SUR is more because network capacity is underutilized due to lack of connection requests. As network load increases, network capacity allocation to primary and backup lightpaths is also increased. Network capacity consumption of backup lightpaths is less because of resource sharing, whereas primary lightpaths must require separate spectrum for serving a request. Hence, SUR decreases when network load increases. The average values of SUR for six cases are shown in Table 3 when network load is concerned. Moreover, it can be seen from Fig. 7(a) and (b) that BSR-MPP is spectrum efficient as compared to SPP and MPP. The spectrum efficiency of BSR-MPP is due to the limited resources that are assigned to backup lightpaths and remaining bandwidth is assigned to the provisioning of primary lightpaths. Allocation of network resources for primary lightpaths increase with the network load. Therefore, significant improvements can be achieved in the context of BSR-MPP strategy.

Table 3
Average values of network parameters of Cost239 and NSFNET Topologies.

Network parameter	Cost239					NSFNET				
	SPP	MPP	BSR-MPP			SPP	MPP	BSR-MPP		
			25%	30%	35%			30%	35%	40%
SUR	0.73	0.66	0.41	0.44	0.46	0.89	0.85	0.70	0.78	0.83
FS sharing	1.87	1.90	2.96	2.52	2.25	1.52	1.56	1.79	1.67	1.63
Percentage of accepted request survived by the multipath	–	0.85	6.70	5.44	4.39	–	4.54	6.21	5.58	4.97
Percentage of accepted bandwidth survived by the multipath	–	1.06	8.21	6.74	5.32	–	4.96	8.20	6.54	5.78

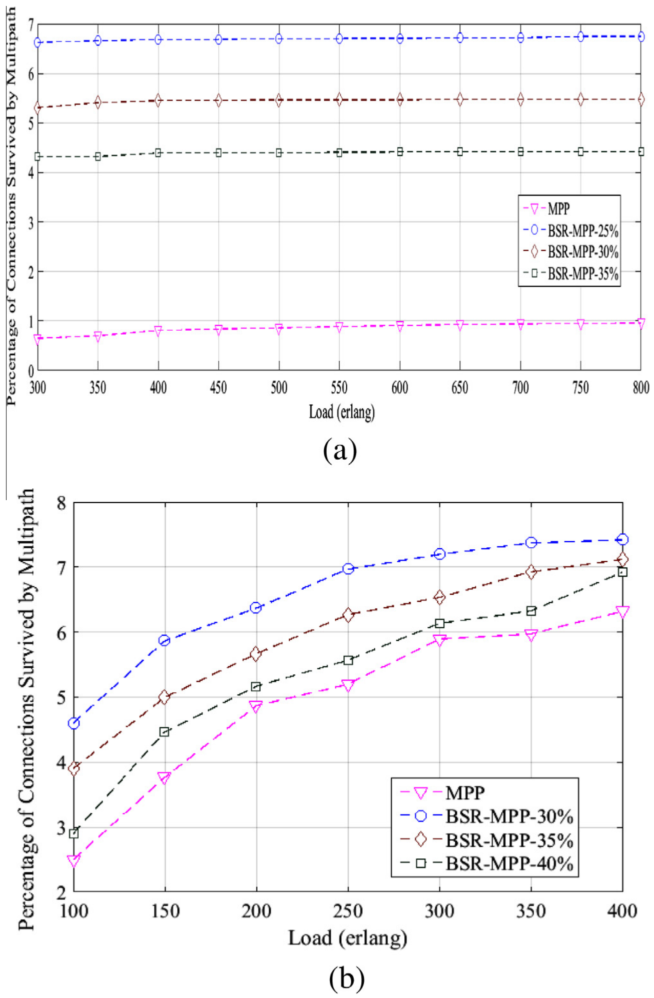

Fig. 9. Percentage of accepted connection requests survived by multipath of (a) Cost239 topology and (b) NSFNET topology.

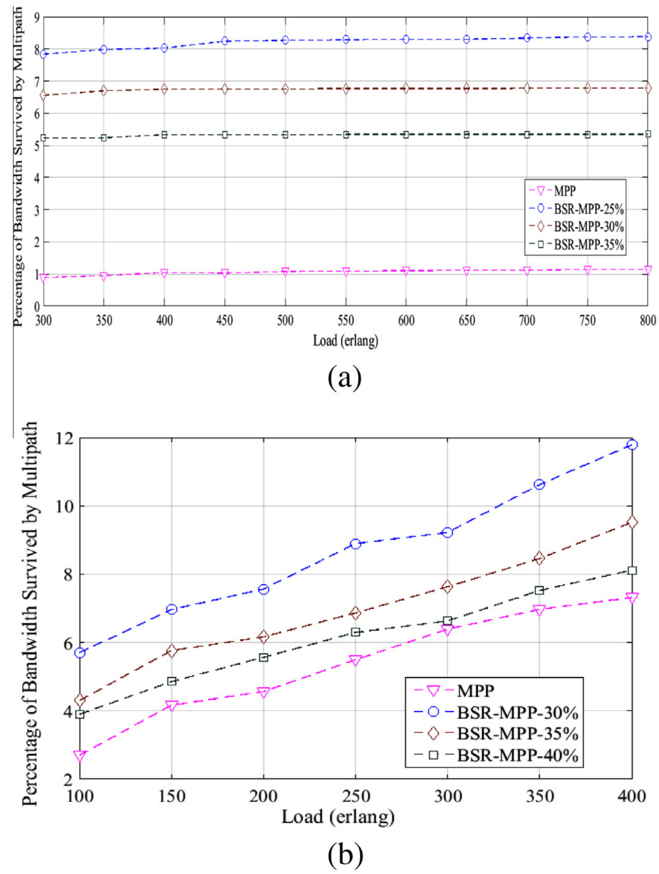

Fig. 10. Percentage of accepted bandwidth survived by multipath in (a) Cost239 topology and (b) NSFNET topology.

Fig. 8(a) and (b) show sharing of an FS with network load. Higher the value of network load, more backup lightpaths are assigned which increases FS sharing. In SPP and MPP, any of the available frequency slots of the total spectrum can be assigned. Therefore, at each time, an idle (i.e., unassigned) FS has an equal assignment possibility of a primary or backup path. However, in BSR-MPP, data of backup lightpaths are carried by the advance reserved backup FSs which result in higher sharing. Sharing of FSs in the context of BSR-MPP varies from 20.32% to 58.28% as compared to SPP and MPP strategies when Cost239 topology is concerned. Similarly, in NSFNET topology sharing of FSs varies from 7.23% to 17.76%. Table 3 summarizes FS sharing for all three strategies.

Fig. 9(a) and (b) show the percentage of accepted connection requests by multiple backup paths. At low network load, network capacity is large enough to satisfy most of the connections by a single backup lightpath (steps 9–13 of Algorithm 1). When network load increases, due to the unavailability of a single backup route, multiple backup routes are searched. In BSR-MPP, spectrum allocation of backup routes is restricted to the assigned bandwidth, whereas in MPP, entire bandwidth is available for the backup route allocation. Therefore, connection survivability with multipath is improved when BSR-MPP is concerned. It can be seen that bandwidth availability of a single backup route is decreased, in BSR-MPP, due to the reduction in backup spectrum allocation. As a result, more connections can be survived by multiple backup routes. Thus, 25% reservation for Cost239 topology and 30% reservation for NSFNET topology show better performances in terms of request survivability with multipath.

Fig. 10(a) and (b) show the percentage of accepted bandwidth survived by multiple backup lightpaths. Multipath bandwidth survivability is defined as the ratio of the bandwidth survived by multipath to the total accepted bandwidth. The performance of EONs is measured based on bandwidth acceptance instead of the number of accepted connection requests. Therefore, Fig. 10(a) and (b) show higher margin of improvement with multipath bandwidth survivability as compared to Fig. 9(a) and (b) where multipath survivability is evaluated based on the number of connection acceptance.

Table 3 summarizes average values of network parameters of the offered load in the context of Cost239 and NSFNET topologies. In Cost239 topology, due to the higher nodal degree, average FS sharing is more than NSFNET topology. On the other hand, more connection requests in NSFNET topology are survived by multipath because of spectrum unavailability on a single backup route. Since backup routes of connection requests in NSFNET topology is longer, lower valued MF is used frequently that result in more spectrum consumption. Use of low MFs in most of the routes in NSFNET topology, as compared to Cost239 topology, results in more connection requests that are survived by multiple backup routes.

5. Conclusion

In this paper we proposed a novel strategy, Backup Spectrum Reservation with MultiPath Protection (BSR-MPP), for survivable Elastic Optical Networks (EONs). BSR-MPP successfully minimizes the problem of spectrum conflict between primary and backup routes. Moreover, for failure recovery, a second backup route can be assigned in BSR-MPP if the first backup route does not have sufficient bandwidth. Furthermore, the advance reservation mechanism increases spectrum sharing than existing strategies such as Shared Path Protection (SPP) and MultiPath Protection (MPP). In particular, BSR-MPP has the advantage of efficient spectrum management with respect to the conventional MPP scheme when multipath routing is concerned. In future, spectrum partitioning to avoid conflict between the primary and backup route assignments can be explored in the context of next generation multicore space division multiplexing EONs.

References

[1] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, S. Matsuoka, Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies, IEEE Commun. Mag. 47 (11) (2009) 66–73.

[2] M. Jinno, B. Kozicki, H. Takara, A. Watanabe, Y. Sone, T. Tanaka, A. Hirano, Distance-adaptive spectrum resource allocation in spectrum sliced elastic optical path network, IEEE Commun. Mag. 48 (8) (2010) 138–145.

[3] Z. Zhu, W. Lu, L. Zhang, N. Ansari, Dynamic service provisioning in elastic optical network with hybrid single/multi path routing, J. Lightwave Technol. 31 (1) (2013) 15–21.

[4] B.C. Chatterjee, N. Sarma, E. Oki, Routing and spectrum allocation in elastic optical networks: a tutorial, IEEE Comm. Surv. Tutor. 17 (3) (2015) 1776–1800.

[5] N. Amaya, G. Zervas, D. Simeonidou, Introducing node architecture flexibility for elastic optical networks, J. Opt. Commun. Netw. 6 (2013) 593–607.

[6] M. Jinno, H. Takara, Y. Sone, K. Yonenaga, A. Hirano, Multiflow optical transponder for efficient multilayer optical networking, IEEE Commun. Mag. 50 (5) (2012) 56–64.

[7] K. Walkowiak, M. Klinkowski, Shared backup path protection in elastic optical networks: modeling and optimization, in: Proc. DRCN, 2013, pp. 187–194.

[8] K.D.R. Assis, R.C. Almedia Jr., H. Waldman, MILP formulation for squeezed protection in spectrum sliced elastic optical path networks, in: Proc. SPECTS, 2012, pp. 1–7.

[9] G. Shen, Y. Wei, S.K. Bose, Optimal design for shared backup path protected elastic optical networks under single link failure, J. Opt. Commun. Netw. 6 (2014) 649–659.

[10] B. Chen, J. Zhang, Y. Zhao, J.P. Jue, J. Liu, S. Huang, W. Gu, Spectrum-block consumption for Shared Path Protection with joint failure probability in flexible bandwidth optical networks, Opt. Swit. Netw. 13 (2014) 49–62.

[11] M. Liu, M. Tornatore, B. Mukherjee, Survivable traffic grooming in elastic optical networks-shared protection, J. Lightwave Technol. 31 (2013) 903–909.

[12] L. Ruan, N. Xiao, Survivable multipath routing and spectrum allocation in OFDM based flexible optical networks, J. Opt. Commun. Netw. 5 (2013) 172–182.

[13] Y. Sone, A. Watanabe, W. Imajuku, Y. Tsukishima, B. Kozicki, H. Takara, M. Jinno, Highly survivable restoration scheme employing optical bandwidth squeezing in spectrum sliced elastic optical path (SLICE) network, in: Proc. Opt. Fiber Comm. Conf., 2009, pp. 1–3.

[14] Y. Sone, A. Watanabe, W. Imajuku, Y. Tsukishima, B. Kozicki, M. Jinno, Bandwidth squeezing restoration in spectrum – sliced elastic optical path networks (SLICE), J. Opt. Commun. Netw. 3 (2011) 223–233.

[15] M. Zotkiewicz, M. Ruiz, M. Klinkowski, M. Pioro, L. Velasco, Reoptimization of dynamic flexgrid optical networks after link failure repairs, J. Opt. Commun. Netw. 7 (1) (2015) 49–61.

[16] L. Liu, W.R. Peng, R. Casellas, T. Tsuritani, I. Morita, R. Martinez, R. Munoz, M. Suzuki, S.J.B. Yoo, Dynamic OpenFlow-based lightpath restoration in elastic optical networks on the GENI testbed, J. Lightwave Technol. 33 (8) (2015) 1531–1539.

[17] F. Paolucci, A. Castro, F. Cugini, L. Velasco, P. Castoldi, MultiPath restoration and bitrate squeezing in SDN-based elastic optical networks, Photonic Netw. Commun. 28 (1) (2014) 45–57.

[18] B. Chen, J. Zhang, Y. Zhao, C. Lv, W. Zhang, S. Huang, X. Zhang, W. Gu, Multi link failure restoration with dynamic load balancing in spectrum-elastic optical path networks, Opt. Fiber Technol. 18 (2012) 21–28.

[19] J. Zhang, B. Chen, Y. Zhao, J.P. Jue, W. Gu, Survivable traffic cognition algorithm with joint failure probability in flexible bandwidth optical networks, China Commun. 10 (4) (2013) 38–48.

[20] T.H. Cormen, C.E. Leiserson, R.L. Rivest, C. Stein, Introduction to Algorithms, vol. 6, MIT press, Cambridge, 2001.

[21] P. Chowdhury, M. Tornatore, A. Nag, E. Ip, T. Wang, B. Mukherjee, On the design of energy-efficient mixed-line-rate (MLR) Optical Networks, J. Lightwave Technol. 30 (2012) 130–138.