Routing and spectrum assignment in MCF-SDM networks

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Abstract: In this paper, we consider a reliable routing and spectrum allocation problem in multi-core fiber space division multiplexing (MCF-SDM) networks. By using MCF-SDM technology, we can overcome the limitations of transmission using single-mode optical fibers. However, in a MCF-SDM network multiple cores are contained in the same cladding and therefore the interference (crosstalk) between cores may occur. Furthermore, transmission path may be broken down due to some unexpectable events. In order to prevent the link failure, we consider to set up a backup path for each working path. A backup path may be dedicated to a working path or be shared with other working paths. In this paper, we consider a reliable routing problem using dedicated path protection (DPP) or shared backup path protection (SBPP) approach in MCF-SDM networks. We formulate the routing problem as an integer linear programming (ILP) problem. We compare the performance of these two protection techniques with the total reserve capacity (FS) and the maximum exponent of the FS. The results show that due to the sharing between backup paths (in the common link of the same core), the SBPP technology requires fewer spectrum resources and spectrum bandwidth than the DPP technology.

Keywords: MCF-SDM network, shared backup path protection, dedicated path protection, integer linear programming problem

1. Introduction

Due to the development of the Internet technologies, the demand of optical transmission capacity and bandwidth are increasing rapidly and the wavelength division multiplexing (WDM) [1] network can not meet the data transmission requirement in the future. To meet the increasing demand, in this thesis we intend to introduce the space-division multiplexing (SDM) network [2] [3]. We also consider the reliability for data transmission. In order to ensure the reliability of the network scientific and reasonable protection path technologies are needed[5]. Among the many protection technologies, shared backup path protection technology is a very efficient and reliable protection technology[4]. Compared with the dedicated path protection technology technology, the SBPP can allow the sharing of spectrum resources on the backup path of the same link[4], which can greatly reduce the cost of network deployment. In [6], the DPP technology and the SBPP technology has been evaluated in single mode fiber network.

In this paper, we consider reliable routing and spectrum assignment in MCF-SDM networks to overcome the transmission limitation of the single mode fiber network. In MCF-SDM networks which should consider the crosstalk effect [8] in data transmission, we intend to evaluate the dedicated path protection technology and the shared backup path protection technology. Then we formulate the DPP problem and the SBPP problem into integer linear programming[7] problems and compare both two protection technologies with the total number spare capacity and the maximal index of used frequency slot (FS) in the networks. In elastic optical networks, frequency slot (FS) refers to the smallest unit of spectrum resources in each fiber. Cause in the real-world transmission, to minimize spare capacity and spectrum bandwidth is much considerable by network operators.

The rest of this paper is organized as follows. In section II, we review the background of SDM technologies and previous researches. In section III, we formulate ILP problems for the reliable routing problems with dedicated path protection and shared backup path protection. In section IV, we perform the numerical experiments and then analyze the experimental results. Finally, section V concludes the paper.

2. Background of this paper

2.1 Space-division multiplexing (SDM) optical networks

Space-division multiplexing (SDM) optical networking is a data transmission technology designed to meet increasing data transmission requirements. Due to the transmission limitation of the current single-mode optical fiber, it is difficult to meet the huge data transmission demand in the future. SDM optical networks are connected by SDM fiber which consists of several single-mode fibers (SMFB) [9], [10], [11], [12] or multi-cores fiber (MCF) [13], [14], [15]. In Fig.1, compared with the single-mode optical fiber, the 4-core SDM fiber which can transmit the data in the 4 spatial dimensions will increase the network capacity to a higher level.

In space-division multiplexing (SDM) optical networks, there

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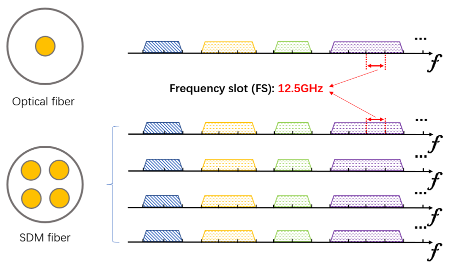

Fig. 1 Single mode fiber and space-division multiplexing (SDM) fiber

are two types of optical fibers: single mode fiber bundle (SMFB) and multi-core fiber (MCF), as shown in Fig.2.

- Single mode fiber bundle (SMFB) As shown in Fig.2 (a), SMFB consists of several single-mode fibers which individually wrapped by optical fiber cladding. In the transmission of data, the cores will not interfere with each other.
- Multi-core fiber (MCF): As shown in Fig.2 (b), MCF is a combination of several cores in an optical fiber cladding, and each core can provide a spatial dimension of data transmission. However, in multi-core fiber, there is an interference called crosstalk, which may affect the transmission quality.

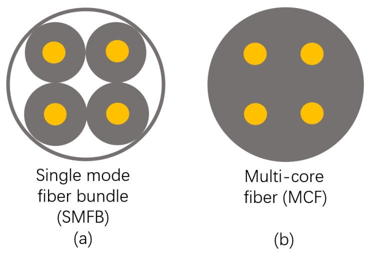

Fig. 2 Single mode fiber bundle (SMFB) and multi-core fiber (MCF)

2.2 Inter-core crosstalk in multi-core fiber

In MCF, the interference called crosstalk [8] may occur between cores and affect the transmission quality. The crosstalk occurs if the same frequency slots are assigned to adjacent cores in a common fiber link to serve different transmission requests. As shown in Fig.3, here is a example of inter-core crosstalk in a 7-core fiber. First of all, we can see that due to the relatively long distance between core.1 and core.3, they are not adjacent cores and will not cause interference. Core.1 (or core.3) and core.2 are adjacent cores due to the distance comparison, crosstalk will occur when the same frequency slots in a common fiber link are used for different requests. On the right side of Fig.3, we can see that because core.1 and core.3 are not adjacent cores, R.1 and R.4 (drawn by the green dashed box) will not cause crosstalk even if the same FSs are used. As for core.2 (drawn by the red dashed box), R.3 and R.1 (or R.5) have the same FSs. Since core.1 (or core.3) and core.2 are adjacent cores, the crosstalk will occur between R.3 and R.1 (or R.5).

In order to reduce the impact of crosstalk, we consider the worst case in this thesis. According to [19], the crosstalk is calculated by Eq.1 where n is the number of adjacent cores, γ is the bend radius, k is the coupling coefficient, β is the propagation constant, and r is the core pitch (see Table. 1). To transmit the

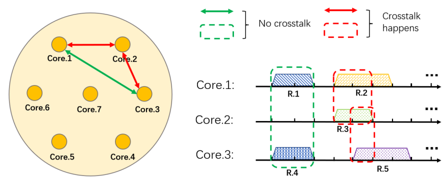

Fig. 3 Example of inter-core crosstalk in a 7-core fiber

data successfully, the crosstalk should be supressed lower than a predefined level (threshold). For example, the crosstalk thresholds used in [17], [18] are shown in Table. 2. Then through calculation, we can get transmission restrictions under thresholds in each modulation as Table.3. In both Table.2 and Table.3, BPSK, QPSK, 8-QAM, and 16-QAM are four different modulation formats in elastic optical networks.

$$XT(L) = \frac{n - n \cdot exp{-(n+1) \cdot 2hL}}{1 + n \cdot exp{-(n+1) \cdot 2hL}}, h = \frac{2k^2 r}{\beta\gamma} \quad (1)$$

Table 1 MCFs features in the simulation

Fiber type	γ (m)	k	β(1/m)	r (m)
4-core	$3.9 * 10^{-5}$	$1.0 * 10^{-3}$	$4.0 * 10^{6}$	$5.0 * 10^{-2}$
12-core	$3.7 * 10^{-5}$	$5.0 * 10^{-4}$	$4.0 * 10^{6}$	$5.0 * 10^{-2}$

Table 2 The crosstalk thresholds in each modulation

	BPSK	QPSK	8-QAM	16-QAM
The crosstalk threshold (dB)	-14	-18.5	-21	-25

Table 3 Transmission restrictions under crosstalk

Transmission restrictions under crosstalk in MCFs (km)	BPSK	QPSK	8-QAM	16-QAM
4-core	38945	13872	7808	3111
12-core	4712	1678	944	376

2.3 Backup path protection technology

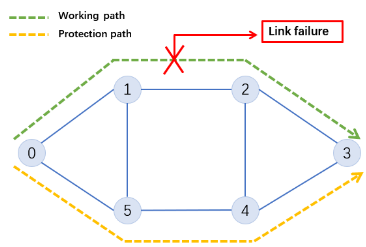

Fig. 4 Link failure in the network

Fig. 4 shows an example of link failure due to some unavoidable reasons. To protect the network from disruption, we need to set up a backup path to restore the failure. This backup path needs to have no common link with the working link. In Fig.4, the working path is 0-1-2-3 and the protection path is 0-5-4-3, there is no public link between these two paths. When the connection failure happens in the working path(0-1-2-3), the protection path(0-5-4-3) will be used to transmit the request. And in this research, we consider the single-link failure in the networks.

2.3.1 Dedicated path protection technology

In dedicated path protection technology [6] [20], for the working path of each request, we consider a corresponding backup path. For each request, both the working and its corresponding protection paths should not have any common link. If multiple backup paths share a common link, the spectra of these backup paths cannot overlap on the common link.

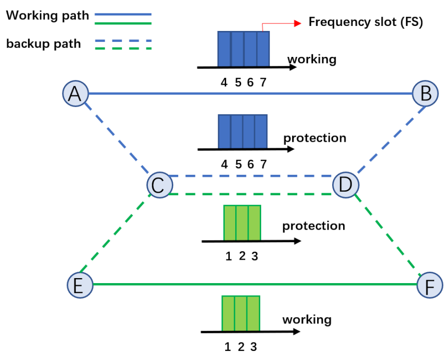

Fig. 5 Dedicated path protection technology

As shown in Fig.5, it is a six nodes simple elastic optical network. The working paths corresponding to protection path (A-C-D-B) and protection path (E-C-D-F) are (A-B) and (E-F) respectively. The protection path (E-C-D-F) needs 3 FSs (index:1,2,3) to recovery the working path (E-F), and the protection path (A-C-D-B) needs 4 FSs (index:4,5,6,7) to recovery the working path (A-B). Figs.6 shows that since there is no sharing spectrum capacity among protection paths in the common link, 7 FSs (Index:1,2,3,4,5,6,7) should be needed in the common link (C-D) by dedicated path protection technology.

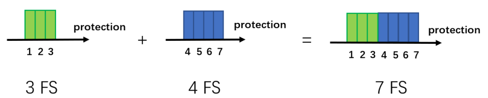

Fig. 6 Spare capacity of dedicated path protection technology

2.3.2 Shared backup path protection technology

In shared backup path protection [6] [21], the backup paths which have a common link can share the spectrum resources, if their corresponding working paths do not share any common link. (Which means, their corresponding working paths are not likely to fail at the same time.)

As shown in Fig.7, the working paths corresponding to protection path (A-C-D-B) and protection path (E-C-D-F) are (A-B) and (E-F) respectively. The working path (A-B) and working path (E-F) do not share any common link, in this case, their corresponding protection paths can share the capacity in the common link (C-D). The protection path (A-C-D-B) and (E-C-D-F) separately need 4 Frequency Slots(FSs) and 3 FSs. Therefore, because of the spectrum capacity sharing in the link (C-D), only 4 FSs are needed for these two backup paths in the common link (C-D) in Fig.8.

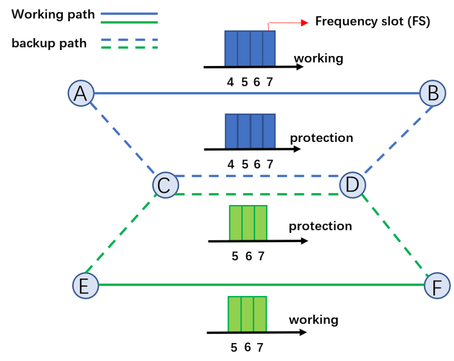

Fig. 7 Shared backup path protection technology

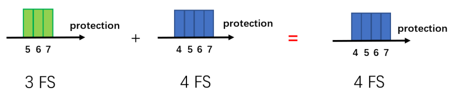

Fig. 8 Spare capacity of shared backup path protection technology

3. Problem formulation

In this section, we formulate the routing and spectrum assignment problem with the shared backup path protection and the dedicated path protection as ILP problems respectively. The objectives of the problems are to minimize the total required spare capacity and the maximum index of FSs with the full recovery of single-link failure. We use the K-shortest path algorithm to decide the working path and corresponding backup paths for each request.

3.1 Routing and spectrum assignment with shared backup path protection

The parameters and variables used here are defined as follows.

- **Set:**

S: set of the network links
C: set of cores in MCF
B_r: set of backup paths of request r
R: set of requests in networks
BL_r:set of links along the backup path of request r
WL_r:set of links along the working path of request r

- **Parameters:**

d_r: Number of FSs required by request r.
M: A large value
λ: A weight factor

- **Variables:**

S^r_w: The starting FS index in the working path of request r.
$S^{r,a}_p$:The starting FS index in protection path a of request r.
$X^{r,a}$:Equals to 1 if the protection path a is chosen for request r; otherwise, equals to 0.
$T^{j,l}$:The total number of reserved FSs for protection path on core l of link j.
$Q^{r,t}_w$:Equals to 1 if $S^r_w > S^t_w$; otherwise, equals to 0.
$H^{r,t,b}$:Equals 1 if $S^r_w > S^{t,b}_p$; otherwise, equals to 0.
$Q^{r,a,t,b}_p$:Equals 1 if $S^{r,a}_p > S^{t,b}_p$; otherwise, equals to 0.
c: The maximal index of FSs which reserved in the network.
$\delta^{r,i}_w$: Equals 1 if working path of request r is affected when link i fails; otherwise, equals to 0.

$Y_p^{r,j,a,l}$:Equals 1 if backup path a of request r crosses core$l$ of link j; otherwise, equals to 0.

$G_w^{r,t}$: Equals 1 if working path of request r and working path of request t share a common core in a same link; otherwise, equals to 0.

$G_{wp}^{r,t,b}$:Equals 1 if backup path b of request t and the working path of request r share a common core in a same link; otherwise, equals to 0.

$G_p^{r,a,t,b}$:Equals 1 if backup path b of request t and backup path a of request r share a common core in a same link, moreover, their corresponding working paths also have a common core in the same link; otherwise, equals to 0.

Our objective is to minimize both the total required spare capacity in the network and the maximal index of used FSs index. The objective function is defined as follows.

$$\text{Minimize} \sum_{j\in S, l\in C} T^{j,l} + \lambda c, \tag{2}$$

where λ is a weighting factor. The constraints of this problem are given as follows.

$$S_w^r + d_r \le c \quad \forall r \in R \tag{3}$$

To ensure that the ending FS index of each request in the working path should be less than the maximal FS index in each link.

$$S_p^{r,a} + d_r \le c \quad \forall r \in R, \forall a \in B_r \tag{4}$$

To ensure that the ending FS index of each request in protection paths should be less than the maximal FS index in each link.

$$\sum_{a\in B_r} X^{r,a} = 1 \quad \forall r \in R \tag{5}$$

To ensure that if the working link of the request r is disconnected, only one protection path is used for transmission recovery.

$$S_p^{r,a} \le M * X^{r,a} \quad \forall r \in R, \forall a \in B_r \tag{6}$$

To ensure that the starting FS index of request r in the protection path is used only when the working link of the request r is disconnected.

$$\sum_{r\in R, a\in B_r} \delta_w^{r,i} \cdot X^{r,a} \cdot Y_p^{r,j,a,l} \cdot d_r \le T^{j,l} \quad \forall i, j \in S, i \ne j \tag{7}$$

To ensure that there is enough spare capacity in core l of link j to satisfy all requests affected by link i and their protection path through core l of link j.

$$S_w^t - S_w^r \le M \cdot (1 - Q_w^{r,t} + 1 - G_w^{r,t}) - 1, \forall r, t \in R, r \ne t \tag{8}$$

$$S_w^r + d_r - S_w^t \le M \cdot (1 - Q_w^{r,t} + 1 - G_w^{r,t}), \forall r, t \in R, r \ne t \tag{9}$$

To ensure if working paths of request r and request t have a common core in the same link, the spectrum of these two requests will not overlap.

$$S_p^{t,b} - S_w^r \le M \cdot (1 - H^{r,t,b} + 2 - X^{t,b} - G_{wp}^{r,t,b}) - 1 \quad \forall r, t \in R, r \ne t, \forall b \in B_t \tag{10}$$

$$S_w^r + d_r - S_p^{t,b} \le M \cdot (H^{r,t,b} + 2 - X^{t,b} - G_{wp}^{r,t,b}) \quad \forall r, t \in R, r \ne t, \forall b \in B_t \tag{11}$$

$$S_p^{t,b} + d_t - S_w^r \le M \cdot (1 - H^{r,t,b} + 2 - X^{t,b} - G_{wp}^{r,t,b}) \quad \forall r, t \in R, r \ne t, \forall b \in B_t \tag{12}$$

To ensure if working path of request r and protection path b of request t have a common core in the same link, the spectrum of these two requests will not overlap.

$$S_p^{t,b} - S_p^{r,a} \le M \cdot (1 - Q_p^{r,a,t,b} + 3 - X^{t,b} - X^{r,a} - G_p^{r,a,t,b}) - 1 \quad \forall r, t \in R, r \ne t, \forall b \in B_t, a \in B_r \tag{13}$$

$$S_p^{r,a} + d_r - S_p^{t,b} \le M \cdot (Q_p^{r,a,t,b} + 3 - X^{t,b} - X^{r,a} - G_p^{r,a,t,b}) \quad \forall r, t \in R, r \ne t, \forall b \in B_t, a \in B_r \tag{14}$$

To ensure if protection path a of request r and protection path b of request t have a common core in the same link, moreover, their corresponding working paths also have a common core in the same link the spectrum of these two requests will not overlap.

3.2 Routing and spectrum assignment with dedicated path protection

The parameters and variables used here are defined as follows.

- **Set:**

S: set of the network links

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BL_r:set of links along the backup path of request r

WL_r:set of links along the working path of request r

- **Parameters:**

d_r: Number of FSs required by request r.

M: A large value

λ: A weight factor

- **Variables:**

S_w^r: The starting FS index in the working path of request r.

$S_p^{r,a}$:The starting FS index in protection path a of request r.

$X^{r,a}$:Equals to 1 if the protection path a is chosen for request r; otherwise, equals to 0.

$T^{j,l}$: The total number of reserved FSs for protection path on core l of link j.

$Q_w^{r,t}$:Equals to 1 if $S_w^r > S_w^t$; otherwise, equals to 0.

$H^{r,t,b}$:Equals 1 if $S_w^r > S_p^{t,b}$; otherwise, equals to 0.

$Q_p^{r,a,t,b}$:Equals 1 if $S_p^{r,a} > S_p^{t,b}$; otherwise, equals to 0.

c: The maximal index of FSs which reserved in the network.

$\delta_w^{r,i}$: Equals 1 if working path of request r is affected when link i fails; otherwise, equals to 0.

$Y_p^{r,j,a,l}$:Equals 1 if backup path a of request r crosses core$l$ of link j; otherwise, equals to 0.

$G_w^{r,t}$: Equals 1 if working path of request r and working path of request t share a common core in a same link; otherwise, equals to 0.

$G_{wp}^{r,t,b}$: Equals 1 if backup path b of request t and the working path of request r share a common core in a same link; otherwise, equals to 0.

$G_p^{r,a,t,b}$: Equals 1 if backup path b of request t and backup path a of request r share a common core in a same link; otherwise, equals to 0.

Here, we intend to minimize both the total required spare capacity in the network and the maximal index of used FSs index. The objective function is defined as follows.

$$\text{Minimize} \sum_{j \in S, l \in C} T^{j,l} + \lambda c, \tag{15}$$

where λ is a weighting factor and the constraints for this problem are given as follows.

$$S_w^r + d_r \leq c \quad \forall r \in R \tag{16}$$

To ensure that the ending FS index of each request in the working path should be less than the maximal FS index in each link.

$$S_p^{r,a} + d_r \leq c \quad \forall r \in R, \forall a \in B_r \tag{17}$$

To ensure that the ending FS index of each request in protection paths should be less than the maximal FS index in each link.

$$\sum_{a \in B_r} X^{r,a} = 1 \quad \forall r \in R \tag{18}$$

To ensure that if the working link of the request r is disconnected, only one protection path is used for transmission recovery.

$$S_p^{r,a} \leq M \cdot X^{r,a} \quad \forall r \in R, \forall a \in B_r \tag{19}$$

To ensure that the starting FS index of request r in the protection path is used only when the working link of the request r is disconnected.

$$\sum_{r \in R, a \in B_r} X^{r,a} \cdot Y_p^{r,j,a,l} \cdot d_r \leq T^{j,l}, \quad \forall j \in S \tag{20}$$

To ensure that there is enough spare capacity in core l of link j to satisfy all requests whose protection path through core l of link j.

$$S_w^t - S_w^r \leq M \cdot (1 - Q_w^{r,t} + 1 - G_w^{r,t}) - 1 \quad \forall r, t \in R, r \neq t \tag{21}$$

$$S_w^r + d_r - S_w^t \leq M \cdot (1 - Q_w^{r,t} + 1 - G_w^{r,t}) \quad \forall r, t \in R, r \neq t \tag{22}$$

To ensure if working paths of request r and request t have a common core in the same link, the spectrum of these two requests will not overlap.

$$S_p^{t,b} - S_w^r \leq M \cdot (1 - H^{r,t,b} + 2 - X^{t,b} - G_{wp}^{r,t,b}) - 1 \quad \forall r, t \in R, r \neq t, \forall b \in B_t \tag{23}$$

$$S_w^r + d_r - S_p^{t,b} \leq M \cdot (H^{r,t,b} + 2 - X^{t,b} - G_{wp}^{r,t,b}) \quad \forall r, t \in R, r \neq t, \forall b \in B_t \tag{24}$$

$$S_p^{t,b} + d_t - S_w^r \leq M \cdot (1 - H^{r,t,b} + 2 - X^{t,b} - G_{wp}^{r,t,b}) \quad \forall r, t \in R, r \neq t, \forall b \in B_t \tag{25}$$

To ensure if working path of request r and protection path b of request t have a common core in the same link, the spectrum of these two requests will not overlap.

$$S_p^{t,b} - S_p^{r,a} \leq M \cdot (1 - Q_p^{r,a,t,b} + 3 - X^{t,b} - X^{r,a} - G_p^{r,a,t,b}) - 1 \quad \forall r, t \in R, r \neq t, \forall b \in B_t, a \in B_r \tag{26}$$

$$S_p^{r,a} + d_r - S_p^{t,b} \leq M \cdot (Q_p^{r,a,t,b} + 3 - X^{t,b} - X^{r,a} - G_p^{r,a,t,b}) \quad \forall r, t \in R, r \neq t, \forall b \in B_t, a \in B_r \tag{27}$$

To ensure if protection path a of request r and protection path b of request t have a common core in the same link, the spectrum of these two requests will not overlap.

3.3 Numerical experiments and performance analyses

We evaluate the performance of the dedicated path protection and shared backup path protection approaches for two network models shown in Fig. 9 and Fig. 10. Fig. 9 is a simple network (n6s9) model with 6 nodes and 9 links. On the other hand, Furthermore, Fig. 10 is a complex network (NSF) model with 14 nodes and 21 links.

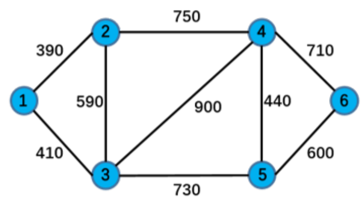

Fig. 9 A network model with 6 nodes and 9 links (n6s9)

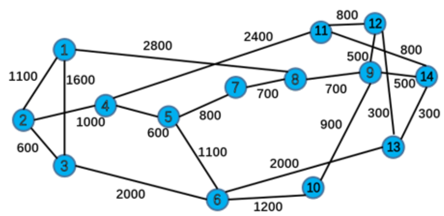

Fig. 10 A network model with 14 nodes and 21 links (NSF)

The demand of each request, say, the number of frequency slots (FSs) needed by a request is randomly chosen between 2 and U, where U is set to be 10, 12, and 14. For the routing, we use the K-shortest path algorithm to decide a working path for each request. Then we also decide three protection paths for each request by the same algorithm. Moreover, the protection paths for each request have no common core in the same link with their corresponding working paths.

The ILP models we build in section 3 can be solved by using optimization tools. In this thesis, we use a soft called AMPL/Gurobi (version is 9.1.1) which run on a win64 machine with 16 physical cores and 32 logical processors to solve the both ILP models. We assume that all the MIPGAPs for corresponding ILP models are less than 0.01% and the running time is the calculation time of Gurobi.

3.4 Experiments in n6s9 network model

In the n6s9 model, we use 20 requests in both the DPP ILP model and the SBPP ILP model. Each request size is between 2 FSs and *U*FSs (*U* equals to 10, 12, and 14). After the computation, we can get the maximal FS index used in the network, the total number of spare capacity (FSs) in the whole network, and the running time. Table.4 is the results of DPP model and table.5 is the results of SBPP model in the n6s9 network.

Table 4 The results of DPP model in the n6s9 network

U	The maximal index of used FSs(c)	The total number of spare capacity(FSs)	Running time(s)
10	20	261	0.23
12	24	274	0.35
14	33	394	0.46

Table 5 The results of SBPP model in the n6s9 network

U	The maximal index of used FSs(c)	The total number of spare capacity(FSs)	Running time(s)
10	19	213	0.50
12	22	237	0.50
14	28	314	0.49

From Figs.11 and 12, we can see that the total number of spare capacity (FSs) increases with the increase of re requests size. And in each set of the *U*, the total number of spare capacity (FSs) in the SBPP model is less than it is in the DPP model. Compared with the SBPP model, the DPP model whose maximal FS index used in the network is much greater needs more spectrum bandwidth. Because of the sharing of the protection paths in the same core of the common link, the SBPP can save much spare capacity and spectrum bandwidth. In addition, if we set a larger request size, the saved backup resources and spectrum bandwidth will be more, because then more FS will be shared between requests.

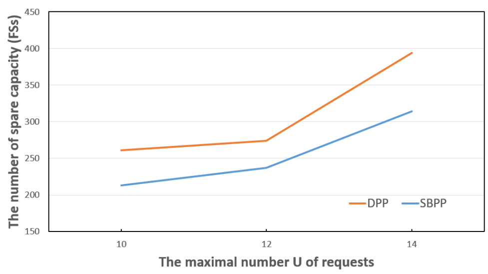

Fig. 11 The total number of spare capacity(FSs) in the n6s9 network

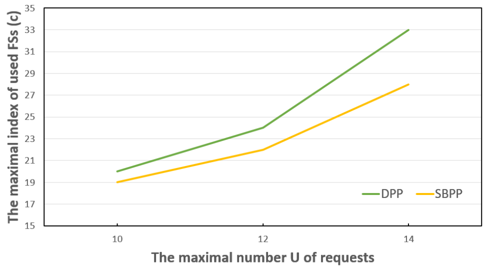

Fig. 12 The maximal index of used FSs (c) in the n6s9 network

3.5 Experiments in NSF network

In the NSF model, we use 100 requests in both the DPP ILP model and the SBPP ILP model. Each request size is between 2 FSs and *U* FSs (*U* equals to 10, 12, and 14). After the computation, we can also get the maximal FS index used in the network, the total number of spare capacity (FSs) in the whole network, and the running time. Table.6 is the results of DPP model and table.7 is the results of SBPP model in the NSF network.

Table 6 The results of DPP model in the NSF network

U	The maximal index of used FSs(c)	The total number of spare capacity(FSs)	Running time(s)
10	51	2040	53.60
12	57	2333	40.53
14	58	2580	32.86

Table 7 The results of SBPP model in the NSF network

U	The maximal index of used FSs(c)	The total number of spare capacity(FSs)	Running time(s)
10	42	1135	296.30
12	52	1349	123.31
14	55	1429	364.13

From Figs.13 and 14, we see that the SBPP can save much spare capacity and spectrum bandwidth because the protection paths can share the same core of the common link similar to the n6s9 model. In addition, in the NSF network, the SBPP model can save more spare capacity and spectrum bandwidth, compared to the n6s9 network. Because the average nodal degree of the NSF network is greater than the n6s9 network, more protection paths can share spare capacity and the SBPP model will perform better.

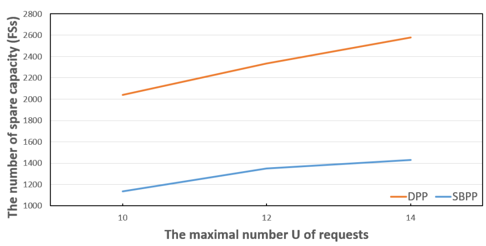

Fig. 13 The total number of spare capacity(FSs) in the NSF network

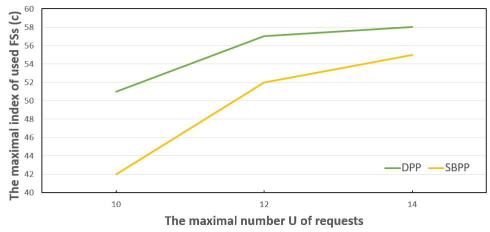

Fig. 14 The maximal index of used FSs (c) in the NSF network

4. Conclusion

In this paper, we considered reliable routing and spectrum assignment with both the DPP and SBPP technologies in MCF-SDM networks. We formulated these problems as two ILP problems. By using an optimization tool called Gurobi Optimizer, we carried out the performance evaluation for these two technologies. From the results, we see that due to the sharing among backup paths (have the same core in the common link), the SBPP technology needs fewer spectrum resources to recovery the link failure. Moreover, when the nodal degree of the network is higher, more spectrum resources can be saved.

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