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The Survivable RBCMLSA Problem on EONs*

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Benefiting from the development of digital signal processing, innovative optical transceivers enable the dynamic adaptation of the baud rate, modulation level and forward error correction (FEC) coding to the optical transmission properties. Next generation optical networks will require high levels of flexibility, being able to fit rate, bandwidth, FEC coding and optical reach requirements of different connections. In this paper, the Survivable Routing, Baud rate, FEC Coding, Modulation Level, and Spectrum Allocation problem (Survivable RBCMLSA) on *Elastic Optical Network* (EON) is defined and studied. The *Dedicated Path Protection* (DPP) and *Shared Backup Path Protection* (SBPP) schemes are considered in this article. Several survivable routing algorithms are proposed to solve this problem. The proposed algorithms are examined through simulations and the results show that the proposed algorithms can achieve good results.

Keywords: survivable RBCMLSA, flexible transceiver, elastic optical network (EON), Dedicated Path Protection (DPP), Shared Backup Path Protection (SBPP)

1. INTRODUCTION

It is believed that the next generation Internet will base on the *Elastic Optical Network* (EON) because of its flexibility and efficiency. The spectrum of a fiber on an EON is divided into several *frequency slots* (FSs) and the necessary amount of consecutive FSs are allocated to support the request from upper layers [1, 2]. The number of required FSs of the connection is determined by the required bandwidth, the signal modulation format (related to the transmission distance), the fixed slice width and Guard Bands (GBs) introduced to separate two spectrum adjacent connections, among others. A key feature of EON is that the modulation format and the allocated spectrum can be adjusted according to the transmission distance and bandwidth requirements.

In EONs, the rate of the transmitter signal ranges from 2.5 Gb/s to 400 Gb/s. Moreover, benefiting from the development of digital signal processing, innovative optical transceivers enable the dynamic adaptation of the baud rate, modulation level and *Forward Error Correction* (FEC) coding to the optical transmission properties. Next generation optical networks will be able to fit rate, bandwidth, and FEC coding and optical reach requirements of different connections. The controller should find a suitable routing path, modulation format, and spectrum for the connection request.

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1.1 FEC and RCMLSA Problem

In an optical network, the Optical Signal to Noise Ratio (OSNR) of a high data rate optical signal would degrade significantly over long transmission distance. This degradation can be overcome by using the FEC coding techniques [3-5]. In FEC coding, redundant *overhead* (OH) bits are attached to the information bits to extend the transmitting distance of the signal. The evolution of FEC technologies can be classified into three generations [3-5]. The first generation used block codes; a typical example is Reed-Solomon (RS) [255, 239]. The second generation used concatenated codes, an example is RS[255, 239] + Bose-Chaudhuri-Hocquenghem (BCH) [1023, 963]. The third generation used the more powerful Soft-Decision (SD) decoding technique; the Block Turbo Code (BTC) and Low-Density Parity Check (LDPC) code are two representatives of this generation. In [6, 7], the new version of FEC coding scheme, named as *Time-Frequency Packing* (TFP) [8] was considered. In [9], authors considered the *Routing, Code, Modulation Level and Spectrum Assignment* (RCMLSA) problem. In RCMLSA problem, not only the route and spectrum, but also the pair FEC code-modulation format best suited are selected to establish an optical connection in EONs. In [9], based on the provided data rates, modulation formats (BPSK/QPSK/8QAM/16QAM/32QAM/64QAM) and different FEC codes (non-FEC and three types of FEC). They proposed an algorithm to determine the route/modulation level/FEC type to minimize the number of required FSs for the connection request. Simulating results showed that the blocking probability of the RCMLSA model is lower than that of the previous simpler models. However, in [9], the baud rate of the transceiver was fixed and cannot be selected by the network controller.

1.2 RBCMLSA Problem

In our previous study, a new dynamic routing problem on EONs with flexible transceivers is defined and studied [10]. It was named as Routing, Baud rate, FEC Coding, Modulation Level, and Spectrum Allocation (RBCMLSA) problem. In the given EONs, the parameters of transceivers can be determined and selected by the network controllers. For a given EON and a sequence of connection requests, the goal is to find lightpaths and assigned suitable channels to lightpaths and meet the traffic and transparent reach (TR) requirement such that the performance measure can be optimized. Unlike previous works in routing model on EONs, the proposed algorithm selects the routing path and spectrum, baud rate, FEC type, and the modulation format best suited to establish an optical connection. In [10], both the single and multipath routing schemes were considered. The blocking performance of the algorithm for the RBCMLSA model is better than the RCMLSA model.

1.3 Survivable Routing Problem

In the traditional *Wavelength Division Multiplexing* (WDM) networks, network survivability has been extensively studied; several various network protection techniques have been proposed in [11]. The path-protection techniques can be divided into the categories of *Dedicated Path Protection* (DPP) and *Shared Backup Path Protection* (SBPP) [11]. DPP means that there is a dedicated backup capacity to protect primary capacity. In contrast, SBPP means that the protection capacity can be shared among multiple protection lightpaths as long as their corresponding primary lightpaths do not fail simultaneously. Because of capacity sharing, the SBPP scheme is generally more capacity efficient than the DPP scheme [11].

In the case of static traffic demand in EON, Klinkowski *et al*. [12] focused on the Routing and Spectrum Assignment (RSA) problem with DPP scheme. In the RSA problem, the TR and modulation format of the lightpath were fixed, that is, it is the simplest routing model in EONs. Shao *et al*. [13] studied the SBPP-based routing problem in EONs for RSA model. A heuristic algorithm was proposed to solve this problem.

For the Routing and Modulation Level and Spectrum Assignment (RMLSA) model, the TR and the modulation format of lightpath are considered [14-17]. For a survivable connection, the modulation formats of the primary and backup paths can be different, and they depend on the TR of the signal. Thus, the number of allocated FSs of these two paths may be different. In [14], the authors studied the path-protection problem on EONs with distance-adaptive modulation formats. For the static traffic, they proposed a Linear Programming model and used the column generation technique to solve the protection problem. In [15], authors considered the survivable routing problem in EONS for SBPP scheme under dynamic traffic. The proposed method is a two-step approach; it includes path routing step and spectrum assignment step. For the spectrum assignment step, three heuristic algorithms were proposed. In [16], authors considered the survivable routing problem in EONs with SBPP scheme. A *Spectrum Window Planes* (SWPs)-based RSA algorithm was proposed to establish the working and protection lightpaths. In [17], authors considered the survivable scheduling problem in EONs with RMLSA model.

According to the survey by authors, only one article took the FEC coding together with survivable routing into consideration [18]. In [18], authors considered SBPP-based EONs with the adaptive FEC allocation strategy for the RSA model. They developed an integer linear programming optimization model as well as an SWPs-based heuristic algorithm to maximize the protected network capacity and minimize the reserved protection capacity. The results showed that the adaptive FEC allocation strategy is very effective in significantly increasing the network capacity of an EON [18]. In [19], the authors focused on the *Regenerator sharing, Adaptive Modulation, Routing, and Spectrum assignment* (RMRS) problem (but without FEC) in an SBPP-based EON. An efficient heuristic algorithm was developed for the RMRS problem to maximize regenerator and spectrum sharing among protection lightpaths with the joint consideration of modulation format and spectrum conversion capabilities of each traversed regenerator along a lightpath.

1.4 Studied Problem and Major Contributions

The DPP and SBPP path-protecting techniques are both popular and practical for EONs. Adaptive baud rates, modulation formats, and FEC allocation strategies have also been shown to be effective for EON operated without network protection [10]. However, no studies exist to combine the RBCMLSA model for an EON with DPP and SBPP-based network protection. This paper combines these two aspects to study the RBCMLSA problem in an EON with DPP and SBPP path protections, which is much more complex than the existing studies that only consider a simpler aspect.

In this paper, the Survivable RBCMLSA problem on EONs with flexible transmitters is studied. For a given EON and a sequence of survivable connection requests, the goal is to establish a pair of link-disjoint primary and backup lightpaths and assigned the suitable number of FSs to the lightpaths to meet the traffic requirement of each request such that the performance measure can be optimized. In this paper, the single-link failure case is studied. For the primary and backup lightpaths of the request, the baud rate, FEC coding type, and modulation format of the lightpath should be determined according to the request and the network status. Moreover, the available FSs are allocated to the lightpath. The DPP and SBPP schemes are considered in this article. This is the first article studied the survivable RBCMLSA problem. By considering the baud rate, the studied problem is more complex than the survivable RMLSA [16] and survivable RCMLSA problems [18].

For the DPP scheme, a heuristic algorithm, named as *Survivable Path Routing Algorithm* is developed. For the SBPP scheme, two approaches are used to find the backup path of the given primary path, they are *Candidate-Path Approach* (CPA) and *Layered-Graph Approach* (LGA). The proposed algorithms have been examined through simulations and the results show that the proposed algorithms can achieve lower blocking probability.

The rest of the paper is organized as follows. First, in Section 2, the definition and assumptions of the problem are given. In Section 3, the Survivable RBCMLSA problem for DPP scheme is solved. In Section 4, the Survivable RBCMLSA problem for SBPP scheme is solved. Then, in Section 5, the performance of the proposed methods is examined. The conclusion is drawn in Section 6.

2. PROBLEM DEFINITION

In this section, the definition of the survivable RBCMLSA problem is given.

2.1 Assumptions

The assumptions of the studied problem are described as follows.

- For each link, there is a fiber connecting the end-nodes and signal can be transmitted bidirectionally.
- All nodes in the network are equipped with spectrum selective switches (SSSs) and bandwidth variable transmitters (BVTs).
- For simplicity, the numbers of FSs provided by links are all equal.
- A GB should be allocated to separate two spectrum adjacent lightpaths.
- Only the single-edge failure case is considered in this paper.

2.2 Constraints

Five constraints are considered in this paper, they are *spectrum continuity constraint*, *subcarrier consecutiveness constraint*, *non-overlapping spectrum constraint*, *link-disjoint constraint for primary and backup paths*, and *transparent reach constraint*. Due to space limitation, the definition of these constraints can be found in [1].

2.3 Notations

- $G = (V, E, l)$: the physical topology of the network, where V is the set of nodes ($|V| = n$), E is the set of links ($|E| = m$), and $l(e)$ is the distance (kilometers) of the link $e \in E$. For each link, W FSs are provided.
- $r = (s, d, BW_{sd})$: the connection request, where $s \in V$ and $d \in V$ is the source and destination node of the request, respectively. BW_{sd} is the required bandwidth (Gb/s) of the request between nodes s and d.
- B: the set of baud rates provided by the transceiver.
- M: the set of possible modulation formats, where M= {PM-QPSK, PM-8QAM, PM-16QAM, PM-32QAM, PM-64QAM}.
- ML_m: the modulation level of the m^{th} modulation format; ML_1=2 (for PM-QPSK), ML_2=3 (for PM-8PSK), ..., $ML_m = m$+1;

- F: the set of possible FEC types.
- $R_{sd} = \{R_{sd}^1, R_{sd}^2, ..., R_{sd}^k\}$: the set of k routing paths between s and d. This set can be computed by performing the k-shortest path algorithm (or Eppstein algorithm) [20] in $O(|E| + k|V| + |V|log|V|)$ time.
- $dist(R_{sd}^i)$: the distance of the path $R_{sd}^i \in R_{sd}$.
- $hop(R_{sd}^i)$: the number of hops of the path $R_{sd}^i \in R_{sd}$.
- $OH[b,f,m]$: $OH[b,f,m]$ represents the required overhead of the transmitting parameters $[b,f,m]$, where $b \in B$, $m \in M$, and $f \in F$.
- $D[b,f,m]$: D is a three-dimension matrix, the element $D[b,f,m]$ represents the TR of the transmitting parameters $[b,f,m]$, where $b \in B$, $m \in M$, and $f \in F$.
- $FM(R_{sd}^i)$: a set of feasible parameters (b,f,m) of the path R_{sd}^i, where, the TR of the parameter (b,f,m) is equal to or higher than the length of routing path $dist(R_{sd}^i)$, *i.e.*, $FM(R_{sd}^i) = \{(b,f,m)\ |dist(R_{sd}^i) \leq D[b,f,m]\}$, where $b \in B$, $m \in M$, and $f \in F$.

The value of $OH[b,f,m]$ is independent with the b and m, it is determined by the type $f \in F$. For FEC type $f \in F$, the OH is selected from {0.0%, 6.69%, 13.34%, 21.2%, 66.66%} for the set of FEC types {No-FEC, Type 1 with RS[255,235], Type 2 with RS[255,239]–BCH[1023,963], Type 3 with LDPC[416,3431,0.825], type 4 with rate-adaptive RS code}. Each flexible transceiver is assumed capable of operating with five modulation formats, five FEC coding levels, and several possible baud rates (shown in Table 1). For example, if the PM-QPSK format is selected, baud rate b is set to 28, and type4 FEC is used, then TR is 2674 km. For a connection request, if the path with distance 2673 km is selected, then transmitting parameters {(28, type4, PM-QPSK), (30, type4, PM-QPSK), (32, type4, PM-QPSK) } can satisfy the transparent reach constraint.

After selecting the routing path $R_{sd}^i \in R_{sd}$, the number of required FSs of the request can be determined by using parameters b, f, m. That is, if the request is supported by a single lightpath, the minimal number of required FSs of the lightpath (denoted as N_{sd}) can be computed by

$$N_{sd} = \left\lceil \frac{BW_{sd} \times (1 + OH[b,f,m])}{C_f \times ML_m} \right\rceil + GB, \tag{1}$$

where C_f is the bandwidth (Gb/s) provided by each FS. For example, if the parameters (b, f, m)= (28, type4, PM-QPSK) is selected and BW_{sd} is (10/40/100) Gb/s, The number of required FSs is (1, 3, 7). In this article, the C_f is set to 12.5 GHz and GB =1.

2.4 RBCMLSA Algorithm

In this section, the details of the single path routing algorithm for the RBCMLSA problem proposed in [10] are improved and described. For the connection request $r = (s,d,BW_{sd})$, the k-shortest paths algorithm [20] is performed on the network $G(V,E,l)$ to find a set of candidate paths $R_{sd} = \{R_{sd}^i, i = 1,2,...,k\}$. For the path, $R_{sd}^i \in R_{sd}$, all feasible transmitting parameters (which satisfy the TR constraint) are found from the Table 1. Then, the best transmitting parameter (b, f, m) is selected and associated with the path. Assume fs_i be the minimum number of FSs required for the path $R_{sd}^i \in R_{sd}$ by

Table 1. The TR for the selected parameters on RBCMLSA model.

$D[b,f,m]$		FEC Type f				
m	b	no-FEC	Type 1	Type 2	Type 3	Type 4
PM-QPSK	28	1674	1774	1874	1992	2674
	30	1856	1956	2056	2174	2856
	32	2084	2184	2284	2402	3084
PM-16QAM	28	1064	1164	1264	1382	2064
	30	1134	1234	1334	1452	2134
	32	1216	1316	1416	1534	2216
PM-QPSK	112	1122	1222	1322	1440	2122
	120	1201	1301	1401	1519	2201
	128	1292	1392	1492	1610	2292
PM-8QAM	75	1011	1111	1211	1329	2011
	80	1075	1175	1275	1393	2075
	85	1147	1247	1347	1465	2147
PM-16QAM	56	920	1020	1120	1238	1920
	60	972	1072	1172	1290	1972
	64	1031	1131	1231	1349	2031
PM-32QAM	45	844	944	1044	1162	1844
	48	888	988	1088	1206	1888
	51	937	1037	1137	1255	1937
PM-64QAM	37	765	865	965	1083	1765
	40	801	901	1001	1119	1801
	43	840	940	1040	1158	1840
PM-32QAM	112	724	824	924	1042	1724
	120	756	856	956	1074	1756
	128	791	891	991	1109	1791
PM-64QAM	93	665	765	865	983	1665
	105	692	792	892	1010	1692
	117	722	822	922	1040	1722

using the best transmitting parameter and $hop(R^i_{sd})$ be the number of hops of the path R^i_{sd}. Paths in R_{sd} are sorted in increasing order according to the weighted value $hop(R^i_{sd}) \times fs_i$ and stored in the priority queue PQ. This is an improvement of the previous algorithm proposed in [10] which selects the shortest path.

All paths in PQ are selected and examined one-by-one in order, the first-fit spectrum allocation approach is used to allocate the required number of FSs along the path if possible. If the spectrum allocation algorithm return successfully, the found resources are allocated. Otherwise, a new candidate path in PQ is analyzed. If no more candidate paths are available in PQ, then the request $r = (s, d, BW_{sd})$ is blocked. The details of the RBCMLSA algorithm are shown in Algorithm 1.

Algorithm 1 : RBCMLSA Algorithm [10]

```
Input : G(V,E,l), r = (s,d,BW_sd);
Output: working lightpaths p_w and parameters b, f, m;
perform k-shortest path algorithm to find a set R_sd of candidate paths between nodes s and d;
for (R^i_sd ∈ R_sd) do
    construct the list FM(R^i_sd);
    if (FM(R^i_sd) ≠ ∅) then
        select the best triple (b_i, f_i, m_i) in FM(R^i_sd) with the minimum number fs_i of required FSs;
        add path R^i_sd, the associated transmitting parameter (b_i, f_i, m_i), and the weighted value fs_i × hop(R^i_sd) to PQ;
    end if
end for
sort all paths in PQ in increasing order according to the weight fs_i × hop(R^i_sd), ∀R^i_sd ∈ PQ;
while (PQ ≠ ∅) do
    select and remove a path p_i from PQ;
    if (there are fs_i free FSs alone the path p_i on current network) then
        allocate resources to the path p_i with parameters b_i, f_i, m_i;
        return path p_i with parameter (b_i, f_i, m_i) as the working path;
    end if
end while
return false;
```

In this paper, we studied the Survivable RBCMLSA problem. For each connection request $r = (s, d, BW_{sd})$, a pair of link-disjoint primary and backup paths is found to route the demand. The RBCMLSA algorithm is performed as the basic algorithm to find the primary path in the studied problem. In addition, depending on the using protection scheme, the respective backup path is found by the specific algorithm.

3. SURVIVABLE ROUTING FOR DPP SCHEME

In the DPP scheme, for each connection request $r = (s, d, BW_{sd})$, a pair of link-disjoint primary and backup paths is found. For serving the demand, the bandwidth provided by the primary and backup paths should be greater than or equal to BW_{sd} Gb/s. The backup path is dedicated to the primary path. In this section, the *Survivable Path Routing Algorithm* (SPRA) for a new connection request for the DPP scheme is developed.

In the SPRA for DPP scheme (denoted as SPRA-DPP), first, a priority queue PQ of candidate paths is constructed by performing the k-shortest path algorithm. Paths in PQ are sorted in increasing order according to the weighted value $hop(R^i_{sd}) \times fs_i$ described in Section 2.4. Second, all paths in PQ are selected and examined in order. If the examined path cannot be allocated on the current network, then the next candidate path in PQ is selected and examined, repeatedly. Otherwise, the primary lightpath is temporarily allocated. Third, those links passed by the primary path are removed from the network. Then, the Backup Path Finding Algorithm-DPP (BPFA-DPP) is performed to find the backup path of the request in a similar way. The details of the SPRA-DPP and BPFA-DPP are described in Algorithm 2 and Algorithm 3, respectively.

Algorithm 2 : SPRA-DPP

Input : $G(V, E, l)$, $r = (s, d, BW_{sd})$;
Output : primary path p_w and backup path p_b of the request r;
perform **Steps** 3–11 of the **RBCMLSA Algorithm** to construct PQ.
while ($PQ \neq \emptyset$) **do**
    select and remove a path p_i from PQ;
    if (there are fs_i free FSs alone the path p_i on current network) **then**
        set p_i with parameters (b_i, f_i, m_i) as the primary path p_w of the request;
        temporarily allocate resources to the primary path p_i with parameters (b_i, f_i, m_i);
        perform **BPFA-DPP Algorithm** to find the backup path p_b of the request;
        if (p_b can be found) **then**
            allocate FSs for the path p_w and p_b, and **return** p_w and p_b;
        else
            release all FSs allocated to p_w;
        end if
    end if
end while
return BLOCK;

Algorithm 3 : Backup Path Finding Algorithm-DPP (BPFA-DPP)

Input : $G(V, E, l)$, request $r = (s, d, BW_{sd})$, primary path p_w;
Output : backup path p_b of the request;
remove all links on primary path p_w from G to form a new graph $G'(V', E', l)$;
perform **Steps** 3–11 of the **RBCMLSA Algorithm** on $G'(V', E', l)$ to construct PQ;
while ($PQ \neq \emptyset$) **do**
    select and remove a path p_i from PQ;
    if (there are fs_i free FSs alone the path p_i on current network) **then**
        set p_i with parameters (b_i, f_i, m_i) as the backup path p_b of the request;
        return p_b;
    end if
end while
return false;

4. SURVIVABLE ROUTING FOR SBPP SCHEME

In this section, the Survivable RBCMLSA problem for SBPP scheme is considered. In the SBPP scheme, two backup lightpaths, which pass through the same fibers, can share the spectrum resources, if their primary lightpaths are link-disjoint. For the connection $r = (s, d, BW_{sd})$, the primary path is found by performing the SPRA-DPP Algorithm (Algorithm 2) except for the **Step 9**. Two approaches are proposed and used to find the backup path of the given primary path, they are *Layered-Graph Approach* (LGA) and *Candidate-Path Approach* (CPA). The details of the proposed algorithms are described in the following subsections.

4.1 Layered Graph Approach (LGA)

To describe the LGA algorithm, several notations used in this algorithm are listed as follows. Assume the primary path is p_w, and the number of required FSs of the backup path is initially assumed to be $BN_{sd} = N_{sd}$, which is the minimal number of required FSs of the primary path. Let c_z be the basic cost of link $e_z \in E$, which is set to 1 initially. Let c'_z be the dynamic cost of the link e_z and the value of c'_z is determined by the current network state. Let P_b be the set of existing backup paths whose respective primary paths are link-disjoint to the primary path p_w. That is, links passed by any path in P_b can be shared if the allocated FSs are overlapped. It is worth noting that the primary and backup paths can use different starting indices of FSs.

The i–th layered graph is denoted as $BLG^i(V^i, E^i, c)$, where $V^i = V$, $E^i = \{e_z | \sum_{j=i}^{i+BN_{sd}-1} b_z(j) = 0, e_z \in E\}$. Note that $b_z(j)$ is a binary indicator, $b_z(j) = 0$ represents that the j^{th} FS of link e_z is free or only used by backup paths in P_b; otherwise, $b_z(j) = 1$. On layered graph BLG^i, if a path from s to d can be found, then there exists a path with BN_{sd} FSs on G and it can serve as the backup path of the request. To find the backup path with the great resource sharing of the primary path on the current network, for the starting FS index i, the layered graph BLG^i is constructed. The cost of links is dynamically adjusted according to the formula (2), and then the Dijkstra's algorithm is used to find a link-disjoint backup path with the minimum cost on BLG^i.

$$c'_z = \begin{cases} +\infty, & \text{if } e_z \in p_w \\ c_z - \frac{B_{zi}}{BN_{sd}}, & \text{if } ((e_z \notin p_w) \cap (e_z \in P_b)) \\ c_z, & \text{otherwise.} \end{cases} \tag{2}$$

On the layered graph BLG^i, the link having the same link with the primary path cannot be used, the cost of the link is set to +∞. If the link e_z has not been used by any primary or backup path on BLG^i, the cost of e_z is set to c_z. If the link e_z is not passed by the primary path and there are some FSs used by other backup lightpaths whose respective primary paths are link-disjoint to the path p_w, then the cost of link e_z is set to $c_z - \frac{B_{zi}}{BN_{sd}}$. Where $B_{zi} = \sum_{j=i}^{i+BN_{sd}-1} b_z(j)$ is the number of frequency slots of the link $e_z \in BLG^i$ used by some backup lightpaths.

The cost c'_z of link e_z is set to $c_z - \frac{B_{zi}}{BN_{sd}}$ for increasing the resource sharing ratio. In addition, the links that have reserved enough shared backup frequent slots have less link cost. If the backup path traverses these links, then there is no need to reserve new frequency-slots and the frequency sharing can be enhanced.

It is worth noting that, the distance of the backup path found on the layered graph BLG^i may be greater than the transparent reach of the respective transmitting parameters.

That is, the path with best resource sharing may violate the TR constraint of the requiring transmitting parameters. Moreover, the distance of the found backup path may result using different transmitting parameters for the request (for example, different baud rate, modulation level, or FEC), so that the pre-set value BN_{sd} may not appropriate. Thus, after finding the path with greatest sharing, the distance of the path should be checked and the best transmitting parameters of the backup path are selected to compute the number of FSs required for transmitting BW_{sd}. If the number of required FSs is greater than BN_{sd}, then the found path cannot be used as the final backup path. Then, the next layered graph BLG^{i+1} for the same value of BN_{sd} is examined.

If all possible FS intervals $[1, N_{sd} - 1]...[W - N_{sd} + 1, W]$ are examined and the backup path cannot be found, then the value BN_{sd} increases by a positive integer BA and repeat the backup path finding process. The best value of BA will be determined by simulations. Moreover, to speed up the finding process, the FS interval size (or BN_{sd}, the possible number of FSs of the backup path) is increased by BA, and the upper bound of the value BN_{sd} is set as $WT \times BN_{sd}$. The best value of WT will be determined by simulations. From the observation; it is easy to find that the distance of the backup does affect the transmitting parameter and the number of required FSs. If the distance factor can be integrated into the cost of the link in the layered graph, it may easy to find a better backup path. Thus, a real value ALPHA ($0 \leq ALPHA \leq 1$) is introduced. The cost of link e_z is set by the following formula.

$$cost(c_z) = ALPHA \times c'_z + l(e_z) \times (1 - ALPHA). \tag{3}$$

ALPHA set to 1 means that the distance factor is not considered. The best value of ALPHA is determined by simulations. The details of the LGA algorithm are described in Algorithm 4.

Algorithm 4 : Layer-Graph Approach (LGA)

Input : $G(V,E,l)$, connection request $r = (s,d,BW_{sd})$, primary path p_w, WT, BA;
Output : backup path of the request;
remove links on primary path p_w from G to form a new graph $G'(V',E',c)$;
commpte BN_{sd} by using the formula (1) for the best parameters of the primary path p_w;
$y = BN_{sd}$;
while ($BN_{sd} \leq WT \times y$) **do**
  $i = 1$;
  while ($i \leq W - BN_{sd} + 1$) **do**
    construct the layered graph $BLG^i(V^i,E^i)$ of the network G', where $V^i = V'$, $E^i = \{e_z | \sum_{j=i}^{i+NB_{sd}-1} b_z(j) = 0, e_z \in E'\}$;
    set up the cost c_z of link $e_z \in E^i$ according to the formulae (2 and 3);
    perform Dijkstra algorithm on graph $BLG^i(V^i,E^i)$ to find the path p_b;
    if (path p_b can be found) **then**
      find the best parameters (b,f,m) of the path p_b and compute the number N_b of required FSs.
      if ($N_b \leq BN_{sd}$) **then**
        return p_b with transmitting parameter (b,f,m) and starting index i.
      end if
    end if
    $i = i + 1$;
  end while
  $BN_{sd} = BN_{sd} + BA$;
end while
return false;

4.2 Candidate-Path Approach (CPA)

In this subsection, the details of the CPA algorithm are described. In the CPA, a set of candidate paths that are link-disjoint to the primary path is constructed and examined. For the given primary path p_w, first, a new graph $G'(V',E',l)$ is constructed by removing the path p_w from G. Then, a set BR_{sd} of candidate paths is found by performing the k-shortest paths algorithm on $G'(V',E',l)$.

To find the backup path p_b with greater resource sharing, all candidate paths in BR_{sd} are examined. For the selected path $BR^i_{sd} \in BR_{sd}$, the set $FM(BR^i_{sd})$ of all feasible transmitting parameters, which satisfy the TR constraint, are constructed. The best triple (b, f, m) in $FM(BR^i_{sd})$, which requires the minimum number (N_i) of FSs is computed (by the formula (1)) and selected. And then, for all possible FS interval $[z, z+N_i-1]$, z = 1, 2, ..., $W-N_i+1$, on the selected path BR^i_{sd} are examined.

The FS interval $[z, z+N_i-1]$ is checked if it is free (or shareable) for allocating the backup resource of path p_b. Let f_{ez} be the cost of the z^{th} FS of the link $e \in G'$ used as the backup path. If the z^{th} FS is free on the link $e \in BR^i_{sd}$, then f_{ez} is set to 1. If the z^{th} FS is used by other primary paths or backup paths whose primary paths are not link-disjoint to p_w, then f_{ez} is set to ∞. If the z^{th} FS is used by other backup paths whose primary paths are link-disjoint to p_w, then f_{ez} is set to 0. If the FS interval $[z, z+N_i-1]$ can be allocated (free or shareable), that is, the total number of required FSs of the path (denoted as $F^{iz}_{sd} = \sum_z^{z+N_i-1} \sum_{e \in BR^i_{sd}} f_{ez}$) is less than ∞, then the path BR^i_{sd} can be shared.

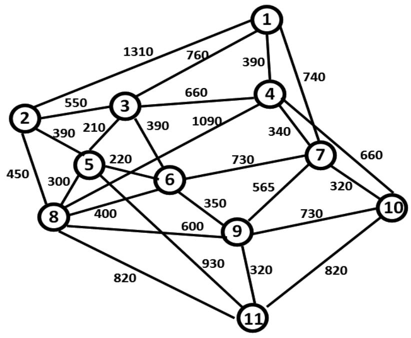
In the CPA, since the distance of the selected candidate path is known, the best transmitting parameters and the number of required FSs can be computed. However, the sharing status of the path on the current network is unknown. Thus, all possible paths and all possible FS intervals should be examined to increase the resources sharing ratio. After examining all candidate paths and all possible FS intervals $[z, z+N_i-1]$, z=1, 2, ..., $W-N_i+1$, the path, which has the smallest value $\min_{z=1,\,2,\,...,\,B-N_i+1;\; i=1,\,2,\,...,\,k}\{F^{iz}_{sd}\}$, is selected as the backup path. The details of the CPA algorithm are described in Algorithm 5.

Algorithm 5 : Candidate-Path Approach (CPA)

Input : $G(V,E,l)$, request $r=(s,d,BW_{sd})$, primary path p_w;
Output : backup path p_b of the request;
remove links on primary path p_w from G to form a new graph $G'(V',E',l)$;
construct the candidate set BR_{sd} of paths by performing the k-shortest path algorithm on $G'(V',E',l)$;
$F^*_{sd} = \infty$;
for (all candidate path BR^i_{sd} in BR_{sd}) **do**
  select and remove a path BR^i_{sd} from BR_{sd};
  construct $FM(BR^i_{sd})$;
  if $(FM(BR^i_{sd}) \neq \emptyset)$ **then**
    select the best triple (b,f,m) in $FM(BR^i_{sd})$ which requires the minimum number N_i of FSs;
    for (all possible staring FS indexes z=1, 2, ..., $W-N_i+1$) **do**
      compute $F^{iz}_{sd} = \sum_z^{z+N_i-1} \sum_{e \in BR^i_{sd}} f_{ez}$;
      if $F^{iz}_{sd} < F^*_{sd}$ **then**
        update R^i_{sd} as the backup path p_b together with the starting FS index and parameters;
        $F^*_{sd} = F^{iz}_{sd}$;
      end if
    end for
  end if
end for
if $(F^*_{sd} < \infty)$ **then**
  return p_b, starting FS index, and parameter (b,f,m);
else
  return false;
end if

5. SIMULATION RESULTS

The proposed algorithms were coded by using the C++ programming language. All simulations were run on a notebook computer with Intel Core i7-4710HQ CPU 2.5GHz,

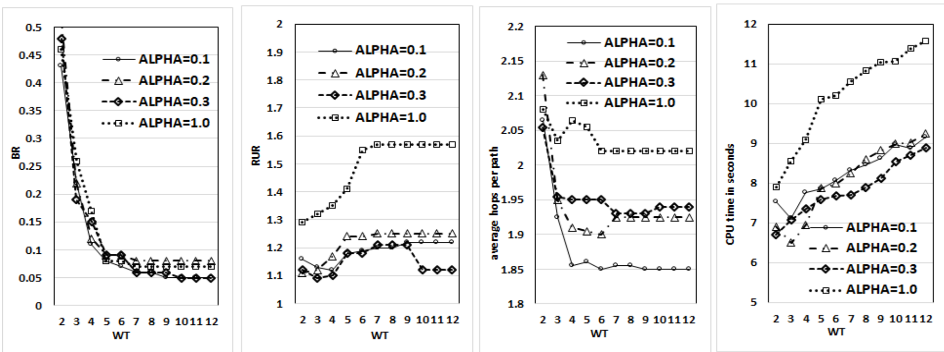


(a)

$D[b,f,m]$		FEC Type f				
m	b	**no-FEC**	Type 1	Type 2	Type 3	Type 4
PM-QPSK	128	**1292**	1392	1492	1610	2292
PM-8 QAM	85	**1147**	1247	1347	1465	2147
PM-16 QAM	64	**1031**	1131	1231	1349	2031
PM-32 QAM	51	**937**	1037	1137	1255	1937
PM-64 QAM	43	**840**	940	1040	1158	1840

(b)

Fig. 1. (a) COST239 network; (b) TR for RCMLSA and RMLSA models.



(a) (b) (c) (d)

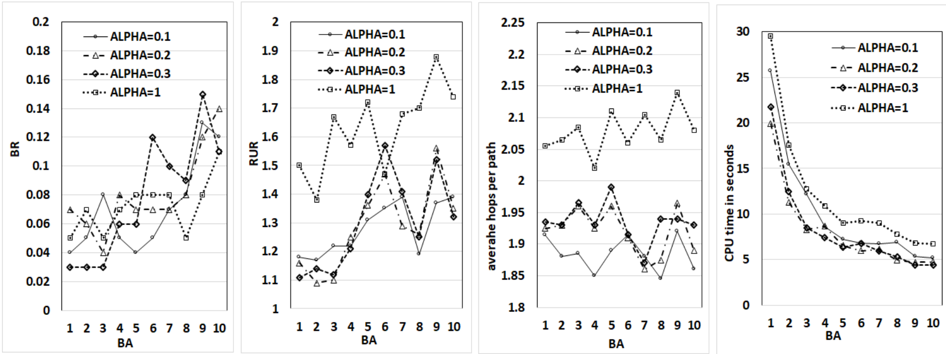
Fig. 2. Effect of parameters ALPHA and WT for LGA algorithm (a) BR; (b) RUR; (c) average number of hops per path; and (d) CPU time.

16.0 Gigabytes RAM and with Windows 10 pro 64-bit operating system. The COST239 network (shown in Fig. 1 (a)) was used for simulations. In Fig. 1 (a), the number nears the link is the length (km.) of the fiber.

The number of candidate paths for a request is $k = 20$. The connection request is randomly generated uniformly for different pairs of nodes, the required bandwidth (Gb/s) is within [10, 2000]. For each fiber of the network, 320 FSs are provided. Several performance criteria are considered in this paper, they are: (1) Blocking Ratio (BR) which is defined as the ratio of the number of blocked connections versus the total number of requests, (2) Resource Utilization Ratio (RUR) which is the ratio of protecting resources to that of the primary resources, (3) average hops per lightpath, and (4) CPU time in seconds.

5.1 Parameters of LGA

In this subsection, the effect of three parameters ALPHA, BA, and WT of the LGA method are determined by simulations. For 100 requests, BA is set to 4, for different values of ALPHA $\{0.1, 0.2, 0.3, 1\}$ and different values of WT, the simulation results are shown in Fig. 2. In Fig. 2 (a), the BR decreases as the value of WT increases. The ALPHA = 0.1 and 0.3 can get the lowest BR in these cases. The results in those cases that WT with values 10–12 is almost the same. In Fig. 2 (b), the RUR varies with different



(a) (b) (c) (d)

Fig. 3. Effect of parameters ALPHA and BA for LGA algorithm (a) BR; (b) RUR; (c) average number of hops per path; and (d) CPU time.

values of WT. The RUR of cases ALPHA=1 is higher than in other cases. This means that by taking the distance factor into consideration, the RUR value can be reduced. The case with ALPHA = 0.3 can get the best RUR results. In Fig. 2 (c), the average hops per path decrease as the value of WT increases for most of the cases. Especially for the range 2–4. The case with ALPHA = 0.1 can get the smallest average hops results and the case with ALPHA =1 can get the largest average hops results. The ALPHA = 0.1 can get the smallest average hops in these cases. For the simulation, the results are shown in Figs. 2 (a)-(c), the value of ALPHA (the distance factor) does affect the results. The value of ALPHA is suggested within 0.1–0.3. In Fig. 2 (d), the CPU time increases as the value of WT increases. The introduction of ALPHA can speed up the computation and the cases with ALPHA =0.3 is the quickest method in most of the cases. The results in those cases that WT with values 10–12 is almost the same.

For 100 requests, WT is set to 9, for different values of ALPHA $\{0.1, 0.2, 0.3\}$ and different values of BA, the simulation results are shown in Fig. 3. In Fig. 3 (a), the BR increases as the value of BA increases for most of the cases. The ALPHA = 0.3 can get the lowest BR in these cases for BA with values 1–3. In Fig. 3 (b), the RUR varies with different values of BA. The RUR of cases ALPHA=1 is higher than in other cases. The case with ALPHA = 0.2 can get the best RUR results. The ALPHA = 0.3 or 0.1 can get the lowest RUR in these cases for BA with values 1–3. In Fig. 3 (c), the average hops per path decreases as the value of BA increases cases BA with values 1–4. The case with ALPHA = 0.1 can get the smallest average hops results and the case with ALPHA = 1 can get the largest average hops results. In Fig. 3(d), the CPU time decreases as the value of BA increases. The introduction of ALPHA can speed up the computation and the cases with ALPHA = 0.3 is the quickest method in most of the cases. The CPU time decreases as the BA value increases. According to the simulation shown above, the BA value is set at 1–3 and the ALPHA value is set to 0.3.

5.2 Comparisons

In this comparison, the static traffic is simulated for a different number of requests ($\{50, 100, 150, 200, 250\}$). The parameters of the LGA are set as BA=1, WT=9, and ALPHA=0.3. The simulation results of the proposed algorithms for the survivable RBCMLSA problem are shown in Fig. 4. Fig. 4 (a) shows that the BR of the CPA is better than the LGA method for the SBPP scheme. And, the BR of the LGA for 50–150

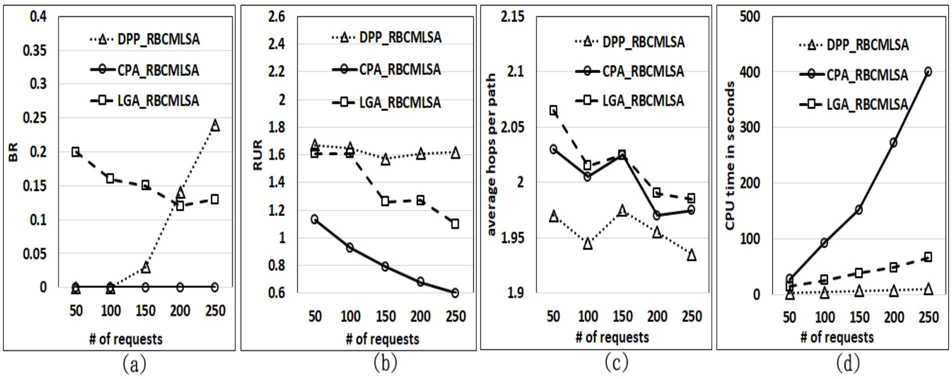


Fig. 4. Simulation results for the RBCMLSA model (a) BR, (b) RUR, (c) average number of hops per path, and (d) CPU time.

requests is worse than the DPP method. Especially, as the number of requests increases, the BR increases for the DPP scheme. Fig. 4 (b) shows the RUR value of CPA is better than that of the LGA and DPP. In most of the cases of the CPA and LGA methods, the RUR value decreases as the number of requests increases, because of more backup resources can be shared and the SBPP scheme makes good use of the backup resources. For the DPP scheme, the RUR value is near about 1.6. Fig. 4 (c) shows the average number of hops per lightpath of the DPP scheme is smaller than that of the other methods. This is because it always uses a shorter path to route the primary and backup paths of requests for the DPP scheme, but in the SBPP scheme, it uses more resource-efficient lightpaths to route the backup lightpaths. Fig. 4(d) shows that the CPU time in seconds of the proposed methods. The CPA is the most time-consuming method, the LGA is quicker than the CPA but the BR is greater than that of the CPA method. The DPP is the quickest and the simplest method. The CPU time increases as the number of requests increases.

In the following, two previous problems, RCMLSA [9] (RBCMLSA without considering baud rates) and RMLSA (RBCMLSA without considering baud rates and FEC types), are considered. The proposed algorithms (SPRA_DPP, LGA, and CPA) were modified to solve the survivable routing on these problems and the results are compared. For the purpose of comparison, the parameters for RCMLSA problem are selected from the central part of the Table 1, the largest TR is selected from parameters with the same modulation format but with different baud rates. The TR of the RCMLSA problem is shown in Fig. 1 (b). For the RMLSA problem, only the non-FEC type is provided, the parameters are shown in the first and third columns (expressed in bold) of the Fig. 1 (b), which are the same as the best parameters for RCMLSA problem but without FEC overhead, the maximum distance is limited by 1292 km. The maximal date rate is limited by 400 Gb/s.

In the DPP scheme, the simulation results for the same static traffic and three models are shown in Fig. 5. The BR for RBCMLSA problem (shown in Fig. 5 (a)) is lower than the RCMLSA and RMLSA problem about 2% and 25%, respectively. This means that the RBCMLSA model is more flexible and more efficient than the RCMLSA and RMLSA models. The RUR of the RBCMLSA model is lower than RCMLSA and RMLSA models for most of the cases (shown in Fig. 5 (b)). For the 150–250 requests, the RMLSA can get shorter lightpaths than the other models (shown in Fig. 5 (c)). For the DPP scheme, the DPP_RCMLSA is quicker than the other models.

In the SBPP scheme, the simulation results for these three models are shown in

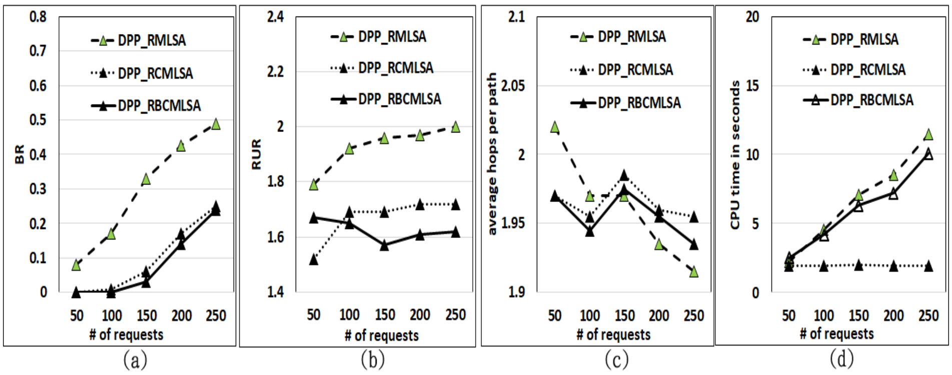


Fig. 5. Simulation results for DPP scheme on three models (a) BR, (b) RUR, (c) average number of hops per path, and (d) CPU time.

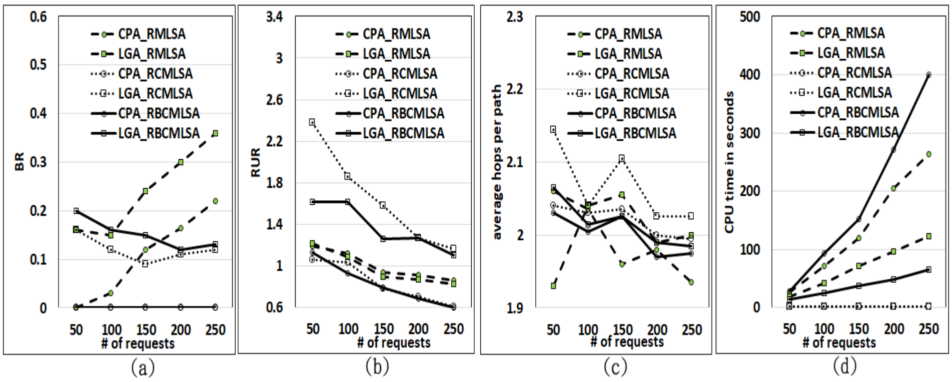


Fig. 6. Simulation results for SBPP scheme on three models (a) BR, (b) RUR, (c) average number of hops per path, and (d) CPU time.

Fig. 6. The BR of CPA_RBCMLSA and CPA_RCMLSA is 0, the CPA method can get a lower BR than the LGA method for all models (shown in Fig. 6 (a)). This means that the RBCMLSA model is more flexible and more efficient than the RCMLSA and RMLSA models. The RUR of the CPA_RBCMLSA and CPA_RCMLSA is lower than other case models for most of the cases (shown in Fig. 6 (b)). And the RUR of the CPA is lower than that of the LGA for all models (shown in Fig. 6 (b)). The average hops per lightpaths of the SBPP schemes are about 1.9–2.2, it is a little higher than that of the DPP scheme (shown in Figs. 5 (c) and 6 (c)). The computation time of the CPA method is higher than the LGA method (shown in Fig. 6(d)).

6. CONCLUSIONS

In this paper, the Survivable Routing, Baud rate, FEC Coding, Modulation Level, and Spectrum Allocation (Survivable RBCMLSA) problem has been defined and studied. For serving survivable transmission on an EON, the goal is to design a survivable routing and spectrum assignment algorithm to establish lightpaths. In the studied problem, two path-protecting schemes (DPP and SBPP) have been considered. For the DPP scheme, a heuristic algorithm has been proposed and for the SBPP scheme, the LGA and CPA algorithms have been proposed. The proposed algorithms have been examined through simulations and the results show that the CPA can achieve the best performance.

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