Benefit of adaptive FEC in shared backup path protected elastic optical network

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Abstract: We apply an adaptive forward error correction (FEC) allocation strategy to an Elastic Optical Network (EON) operated with shared backup path protection (SBPP). To maximize the protected network capacity that can be carried, an Integer Linear Programming (ILP) model and a spectrum window plane (SWP)-based heuristic algorithm are developed. Simulation results show that the FEC coding overhead required by the adaptive FEC scheme is significantly lower than that needed by a fixed FEC allocation strategy resulting in higher network capacity for the adaptive strategy. The adaptive FEC allocation strategy can also significantly outperform the fixed FEC allocation strategy both in terms of the spare capacity redundancy and the average FEC coding overhead needed per optical channel. The proposed heuristic algorithm is efficient and not only performs closer to the ILP model but also does much better than the shortest-path algorithm.

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1. Introduction

Flexi-grid elastic optical networks (EONs) have received extensive interest because of their flexibility in bandwidth allocation and high spectrum efficiency [1, 2]. In this type of network, a bandwidth variable transponder (BVT) generates an optical signal with appropriate modulation methods using only as many subcarriers as are needed to satisfactorily meet the client demands for bandwidth. In an EON, each subcarrier is referred to as a Frequency Slot (FS) [2] and is the basic bandwidth allocation unit in an EON. In such a network, varying the bandwidth, modulation format, and baud rate per channel would allow us to tradeoff the bit rate with the transparent reach of the optical channel. Though we have seen extensive studies on adaptive bandwidth and modulation formats [3], research on the benefits of adaptive FEC allocation has only been reported recently in [4, 5].

Orthogonal frequency division multiplexing (OFDM)-based EONs split a high data rate stream onto several lower symbol rate subcarriers making them more resilient to physical-layer impairments. The optical signal to noise ratio (OSNR) of a high data rate optical signal would degrade significantly over long transmission distances. Forward error correction (FEC) [6–16] coding techniques with low hardware investment cost and high error-correction
performance can effectively compensate for this degradation. This is by adding redundant overhead bits appropriately to the information bits before modulation and transmission. For a system using FEC, there is a direct relationship between the improvement in the net coding gain (NCG) obtained through the FEC and the increase in its coding overhead (OH).

A fixed (or uniform) FEC allocation strategy would tend to choose the best FEC (i.e. with the highest NCG) to adequately cater to the lightpath with the poorest OSNR in the whole network, using this even on lightpaths with higher OSNRs where such high NCGs may not be needed. We had tackled the low efficiency of this fixed FEC allocation strategy by proposing an adaptive FEC allocation strategy for optical channels in [4, 5] to show that the adaptive strategy significantly improves the spectral efficiency of the EON. However, these studies only considered the case without network protection. Since network survivability would be important in high-speed optical transport networks, it would be desirable to apply the adaptive FEC strategy to a scenario where network protection is additionally incorporated in order to further extend the benefits of this adaptive strategy. This will be more complicated if adaptive FEC strategies are applied for both the working and protection lightpaths as these lightpaths would generally have different physical routes, which could correspond to different FEC types.

As survivability is of paramount importance to an optical transport network that carries a large amount of traffic, various protection techniques have been proposed to design survivable elastic optical networks [17–24]. Of the many network protection techniques available, shared backup path protection (SBPP) is considered to be one of the most promising ones due to its combined advantages of operational simplicity, speed, and efficiency. With the SBPP technique, protection lightpaths are allowed to share protection capacity on their common links as long as their corresponding working lightpaths do not share any common link(s). This makes SBPP’s protection capacity sharing very efficient so that it can achieve much higher spectrum resource utilization than other network protection schemes.

In this paper, we consider SBPP-based EONs with the adaptive FEC allocation strategy where our objective is to maximize the carried protected capacity of the network and minimize the protection capacity reserved in it, subject to the limited spectrum resource of each fiber link. For this, we develop an ILP optimization model as well as a SWP-based heuristic algorithm. Performance comparisons of these schemes are made with a standard shortest path (SP)-based algorithm. Comparing the performances of these three approaches, it is evident that the adaptive FEC allocation strategy proposed by us is very effective in significantly increasing the network capacity of an EON.

2. Related works

2.1 FEC technology

FEC technologies were first proposed for fiber-optic communications in [6]. Subsequently, FEC techniques with different error correcting capabilities were studied to evaluate both the performance of different FEC types and corresponding tradeoffs between their Net Coding Gains (NCGs) and their coding overheads (OHs). The first experimental FEC implementation in an optical system used a simple Hamming code and could give a coding gain of only 2.5 dB [6]. As both WDM techniques and coding approaches matured, more complex codes were used for higher coding gains. The most notable of these were the Turbo codes and the LDPC codes [9, 10], where the LDPC code could achieve performance very close to the Shannon limit (i.e., within 0.04dB) [10]. In addition, other techniques such as interleaving, iterative decoding and soft-decision decoding based on multiple thresholds were also developed to further improve error correction performance [11–13].

The future trends expected for FECs to combat even higher transmission impairments were presented in [7, 13] with the evolution of FEC technologies classified into three
generations in [7, 8]. The first generation used block codes, of which a typical example is RS (255, 239) with an NCG (@BER = 10^{-13}) of 5.8 dB. The second generation used concatenated codes with a typical NCG (@10^{-13}) of 7–9 dB (e.g., RS (255, 239) + BCH (1023, 963)). The third generation uses the more powerful Soft-Decision Decoding technique to achieve an NCG (@10^{-13}) of more than 10 dB. Block Turbo Code (BTC) and Low Density Parity Check (LDPC) code are two representatives of this third FEC generation.

Other FEC-based techniques have also been explored for the optical transmission system. To reduce the power consumption of optical links by assigning different types of FECs, Rasmussen et al. [14] demonstrated a scheme that could decrease the number of necessary decoding iterations and thus reduce the power consumption in iterative decoders during periods of low load. In [15], Dorize et al. presented a scheme that could save power consumption at the FEC decoder by adjusting the number of LDPC iterations according to the exact need of each WDM connection in terms of reach and/or Quality of Transmission (QoT). Gho et al. [16] proposed a rate-adaptive transmission scheme using variable-rate FEC codes with a fixed signal constellation and a fixed symbol rate and showed that this can extend the reach of the transmissions even when regeneration sites were not available, thereby helping networks adapt to changing traffic demands. Our previous work [4] was the first to propose adaptive FEC selection for the WDM network, and showed that this was efficient in achieving the lowest average FEC overhead per lightpath. In [5], we extended this adaptive FEC allocation strategy to EONs to show results similar to those obtained for WDM networks. However, neither study considered network protection.

2.2 SBPP technique

Most prior works on SBPP have focused on SDH/SONET networks and, more recently, on Dense Wavelength Division Multiplexing (DWDM) optical networks [25]. Recently, the SBPP technique has also been applied to an EON. We considered the SBPP technique in [23, 24] where we developed an ILP model both to minimize the required spare capacity and maximize the number of link frequency slots (FSs) used. The results there showed that compared with traditional 1 + 1 path protection, the SBPP technique was effective in reducing both the number of FSs needed and the spare capacity redundancy required. A new SBPP-type protection mechanism and an accompanying ILP model were given in [26] where this new mechanism and accompanying model allowed better benchmarking of SBPP-like network designs, and would facilitate further study into the performance of SBPP relative to other network survivability approaches. However, the integer linear program (ILP) design model for SBPP is difficult to solve with reasonable computing and time resources. To reduce the complexity and solution time, Habibi et al. identified the sharing relationship between working and backup capacities in [27] to develop two novel algorithms for minimizing the number of constraints in the ILP models for SBPP in mesh networks. This approach led to a remarkable reduction of around 50% in the number of constraints needed.

To reduce the complexity and solution time of ILP for SBPP, a number of heuristic algorithms have also been developed to provide approximately optimal solutions. Heuristic algorithms and lower bound methods for the SBPP planning problem were proposed in [28]. Experimental results showed that the heuristic algorithms were able to find good quality solutions in minutes. Another work in [29] presented a strategy to indicate that SBPP was a viable option for networks of national dimensions, but that the backup sharing of high availability connections was severely limited in networks of continental dimensions. In [30], the authors formulated RSA/SBPP as an Integer Linear Programming (ILP) problem and proposed several heuristic algorithms including AFA/SBPP, MSALF and also adapted existing RSA methods to the SBPP scenario, they showed that the proposed new algorithms outperformed other reference algorithms. An efficient heuristic algorithm based on spectrum window planes (SWPs) was proposed in [31], which implemented distance and modulation
format adaptive RSA to maximize spare capacity sharing between multiple protection lightpaths.

The SBPP network protection technique is both popular and practical for optical transport networks, including EON. Adaptive FEC allocation strategies have also been shown to be effective for both WDM and EON operated without network protection. However, no studies exist to combine the adaptive FEC allocation strategy for an EON with SBPP-based network protection. This paper combines the two aspects to study the adaptive FEC allocation strategy for the RSA problem in an EON with SBPP network protection, which is much more complicated than the existing studies that only consider either aspect.

3. SBPP-based adaptive FEC strategy

We introduce here the proposed SBPP-based adaptive FEC allocation strategy in the context of an EON. Considering the three FEC generations in in Table 1, we can see that the first generation of FEC, i.e., RS (255, 239), requires the lowest FEC overhead, but achieves the lowest NCG and shows the highest OSNR limit. In contrast, the third generation of FEC, i.e., LDPC (4161, 3431, 0.825), can achieve the highest NCG and therefore requires the lowest OSNR limit at the cost of the highest FEC overhead. The second generation of FEC, i.e., RS (255, 239) + BCH (1023, 963), shows a performance intermediate between the two. These coding techniques show a tradeoff between improvements in NCG or a lower OSNR limit with increasing coding overhead (OH). In general, a higher NCG or a lower OSNR limit requires a higher FEC overhead, and vice versa. Here the OSNR limit is interpreted as the lowest OSNR required for an optical channel to reach a certain bit error rate (BER), e.g., $10^{-12}$ or $10^{-13}$.

<table>
<thead>
<tr>
<th>FEC Types</th>
<th>OH (%)</th>
<th>NCG (dB)</th>
<th>Data Rate (Gbps)</th>
<th>Q Limit</th>
<th>CG</th>
<th>OSNR Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS(255,239)</td>
<td>6.69</td>
<td>5.8(@10^{-13})</td>
<td>106.69</td>
<td>11.2 dB</td>
<td>6.08 dB</td>
<td>14.5</td>
</tr>
<tr>
<td>RS(255,239) + BCH(1023,963)</td>
<td>13.34</td>
<td>7.3(@10^{-12})</td>
<td>113.34</td>
<td>9.0 dB</td>
<td>7.92 dB</td>
<td>12.6</td>
</tr>
<tr>
<td>LDPC(4161,3431,0.825)</td>
<td>21.2</td>
<td>11.27(@10^{-13})</td>
<td>121.2</td>
<td>5.2 dB</td>
<td>12.1 dB</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Based on the three FEC types in Table 1, the proposed SBPP-based adaptive FEC allocation strategy can now be explained in the context of an EON. To highlight the performance benefit of the SBPP-based adaptive FEC scheme, the SBPP-based uniform FEC allocation strategy has also been considered. The example of Fig. 1(a) shows a test network with two working lightpaths 0-1-2-3-5 and 0-7 whose corresponding protection lightpaths are 0-8-6-5 and 0-8-6-7, respectively. Here, lightpath 0-1-2-3-5 has the lowest OSNR (i.e., OSNR_3 = 10 dB) and would need FEC type 3 with the highest NCG (i.e., LDPC (4161, 3431, 0.825)) for establishment. If a fixed FEC assignment strategy is applied for all the lightpaths in the network, then the other three lightpaths will also be assigned the same FEC type. However, it is clearly wasteful and unnecessary to assign FEC type 3 for the three lightpaths 0-7, 0-8-6-5 and 0-8-6-7. In fact, based on the actual lightpath OSNRs, FEC type 1 and type 2 are sufficient to operate lightpaths 0-7, 0-8-6-5 and 0-8-6-7 to reach their respective required BERs. Our proposed adaptive FEC assignment strategy is to use the most efficient, just sufficient FEC type according to the actual OSNR of each lightpath. This would assign FEC type 3 to lightpath 0-1-2-3-5, while FEC type 1 would be sufficient for lightpath 0-7 and FEC type 2 for lightpaths 0-8-6-5 and 0-8-6-7.

We can now estimate the total FEC overheads required by the adaptive and fixed FEC assignment strategies. Assuming each lightpath to need 20 FSs in the example of Fig. 1, if the traditional fixed FEC allocation strategy is applied to all the lightpaths in the network then, since FEC type 3 has a 21.2% overhead corresponding to 5 FSs, the total required overhead for all the lightpaths would be $5 + 5 + 5 + 5 = 20$ FSs. In contrast, if the adaptive FEC
allocation strategy is applied, then the overheads required by the three FEC types are 6.69%, 13.34%, and 21.2%, respectively, and the respective overheads required by each of the four lightpaths would be 2, 3, 3, and 5 FSs. This implies that only a total of 2 + 3 + 3 + 5 = 13 FSs would be required as overhead thus saving 7 FSs as compared to the fixed approach. This shows how the proposed adaptive FEC allocation strategy is effective in reducing the total number of FSs used. In Fig. 1(b) we show how the FSs are assigned to each of the lightpaths when the adaptive strategy is used.

In addition, based on the above spectrum assignment, SBPP only needs to reserve at most 20 FSs on common links (0-8) and (8-6) to guarantee full recovery in case of non-simultaneous failures (e.g., links (0-7) and (1-2)). This is because the two working lightpaths do not share any common link(s) and so spare capacity can be shared on the common links traversed by their corresponding protection lightpaths.

4. ILP model for adaptive FEC allocation strategy

We present next the routing and spectrum assignment (RSA) problem for an EON with SBPP-based adaptive FEC allocation and formulate this with a path-arc ILP optimization model.

4.1 Problem statement

Consider a general EON as the graph \( G(V, E) \), where \( V \) is the set of nodes and \( E \) is the set of (bi-directional) fiber links between node pairs. As given in [4], depending on the length of a fiber link, optical amplifiers are appropriately placed and the OSNR of each route (working or protection) is accordingly calculated. Due to page limit constraints, these procedures have not been detailed here but can be found in [4]. Each fiber link is assumed to have limited FS resources. Over the links between a node pair, a lightpath would need a certain number of FSs for basic operation and extra FSs to account for the FEC overhead. There are also multiple pre-calculated routes used for working and protection lightpath establishment where a working lightpath and its protection lightpath are ensured to be fully link-disjoint. Each lightpath should follow the constraints of spectrum continuity and spectrum contiguity, where spectrum continuity means that the lightpath must be assigned the same set of FSs on all the traversed fiber links and spectrum contiguity means that the FSs that make up the spectrum of a lightpath should be spectrally neighboring.

The optimization objective of the RSA problem is to maximize the effective protected capacity for user data transmission between different node pairs and also to minimize the link protection capacity reserved in the whole network. Solving this optimization gives the following outputs: (1) the network total protected capacity used for actual user data transmission, (2) the assigned FEC type for each established lightpath, (3) the chosen route
and assigned spectrum of each established lightpath, (4) the spare capacity redundancy and (5) the average FEC coding overhead for the respective working and protection lightpaths.

4.2 ILP model

In this part, we present an ILP model for the SBPP-based EON with the adaptive FEC allocation strategy. We assume that a single shortest route between any node pair is used to establish the working lightpath for that pair while other multiple routes between the node pair that are link-disjoint from the working route are candidate routes for setting up a protection lightpath between them. All the OSNRs of each route are pre-calculated in the same way as in [4]. Based on the OSNR values, we also pre-decide the most efficient FEC type for each of the routes. The sets, parameters, variables, and formulation of the ILP model are as follows.

Sets:
- \( L \) The set of links.
- \( D \) The set of node pairs.
- \( R_d \) The set of protection routes between node pair \( d \), each of which is link-disjoint from the corresponding working route.

Parameters:
- \( T_d \) The number of FSs required between node pair \( d \) (without FEC overhead).
- \( K_d \) The extra FSs required on the working lightpath between node pair \( d \) due to FEC overhead.
- \( u^b_d \) The extra FSs required if a protection lightpath is established on the \( b^{th} \) protection route between node pair \( d \) due to FEC overhead.
- \( \eta^d_i \) A binary parameter that equals 1 if the working lightpath of node pair \( d \) is affected when link \( i \) fails; 0, otherwise.
- \( \gamma^d_{b, t} \) A binary parameter that equals 1 if the \( b^{th} \) protection route between node pair \( d \) crosses link \( j \); 0, otherwise.
- \( \varepsilon^d_t \) A binary parameter that equals 1 when the working lightpath of node pair \( d \) and the working lightpath of node pair \( t \) share a common link; 0, otherwise.
- \( \gamma^d_t \) A binary parameter that equals 1 when the working lightpath of node pair \( d \) and protection lightpath \( b \) of node pair \( t \) share a common link; 0, otherwise.
- \( \delta^d_{b, a} \) A binary parameter that equals 1 when protection lightpath \( a \) of node pair \( d \) and protection lightpath \( b \) of node pair \( t \) share a common link and their corresponding working lightpaths also share a common link; 0, otherwise.
- \( C \) The maximum FS index used in the network.
- \( F \) A large value.
- \( \alpha \) A weight factor.

Variables:
- \( \rho^d \) A binary variable that equals 1 if the working lightpath for node pair \( d \) is established; 0, otherwise.
- \( \psi^b_d \) A binary variable that equals 1 if protection route \( b \) of node pair \( d \) is chosen for protection lightpath establishment; 0, otherwise.
- \( w^d \) Minimum number of FSs (including user demand and extra required FEC overhead) required on the working lightpath between node pair \( d \) to accommodate the bandwidth required between node pair \( d \).
- \( p^b_d \) Minimum number of FSs (including user demand and extra required FEC overhead) required on protection lightpath \( b \) between node pair \( d \) to accommodate the bandwidth required between node pair \( d \).
- \( f^d \) An integer variable denoting the starting index of the FSs assigned to the working lightpath between node pair \( d \).
- \( e^d_b \) An integer variable denoting the starting index of the FSs assigned to protection lightpath \( b \) between node pair \( d \).
- \( x^d_t \) A binary variable that equals 1 when the starting FS index of working lightpath between node pair \( d \) is larger than that of the working lightpath between node pair \( t \), i.e., \( f^d > i^d \); 0, otherwise.
- \( y^b_t \) A binary variable that equals 1 when the starting FS index of working lightpath between node pair \( d \) is larger than that of protection lightpath \( b \) between node pair \( t \), i.e., \( f^d > \gamma^d_t \); 0, otherwise.
A binary variable that equals 1 when the starting FS index of protection lightpath \( a \) between node pair \( d \) is larger than that of protection lightpath \( b \) between node pair \( t \), i.e., \( e^{d}_{a} > e^{d}_{b} \); 0, otherwise.

\( S_{j} \)

The number of used FSs on span \( j \) by protection lightpaths, which is the sum of the FSs used for user data transmission and the FSs used for protection lightpath FEC overheads.

**Objective:** Maximize

\[
\sum_{d \in D} \rho_{d} \cdot T_{d} - \alpha \cdot \sum_{j \in L} S_{j}
\]

(1)

**Subject to:**

\[
\rho_{d} = \sum_{b \in R_{d}} \psi^{b}_{d} \quad \forall d \in D
\]

(2)

\[
\sum_{b \in R_{d}} \psi^{b}_{d} \leq 1 \quad \forall d \in D
\]

(3)

\[
\sum_{d \in D, b \in R_{d}} \eta^{d}_{i} \cdot \psi^{b}_{d} \cdot \psi^{r^{d}_{b}} \cdot (T_{d} + u^{b}_{d}) \leq S_{j} \quad \forall i, j \in L, i \neq j
\]

(4)

\[
w^{d} = \rho_{d} \cdot (T_{d} + K_{d}) \quad \forall d \in D
\]

(5)

\[
p^{b,d} = \psi^{b}_{d} \cdot (T_{d} + u^{b}_{d}) \quad \forall d \in D, \forall b \in R_{d}
\]

(6)

\[
C \geq f^{d} + w^{d} \quad \forall d \in D
\]

(7)

\[
C \geq e^{d}_{a} + p^{b,d} \quad \forall d \in D, \forall b \in R_{d}
\]

(8)

\[
f^{d} + w^{d} - f^{t} \leq \nabla \cdot \left( x^{d}_{t} + 1 - e^{d}_{t} \right) \quad \forall d, t \in D, d \neq t
\]

(9)

\[
f^{d} + w^{d} - f^{t} \leq \nabla \cdot \left( x^{d}_{t} + 1 - e^{d}_{t} \right) \quad \forall d, t \in D, d \neq t
\]

(10)

\[
e^{d}_{b} - e^{d}_{a} \leq \nabla \cdot \left( 1 - z^{b,d}_{a} + 3 - \psi^{b}_{d} - \psi^{d}_{a} - \delta^{b,d}_{a} \right) \quad \forall a \in R_{d}, \forall b \in R_{t}, \forall d, t \in D, d \neq t
\]

(11)

\[
e^{b}_{b} + p^{b,d} - f^{d} \leq \nabla \cdot \left( 1 - y^{b,d}_{a} + 2 - \psi^{b}_{d} - \psi^{d}_{a} \right) \quad \forall b \in R_{t}, \forall d, t \in D, d \neq t
\]

(12)

\[
e^{d}_{a} + p^{a,d} - e^{d}_{b} \leq \nabla \cdot \left( 3 - \psi^{b}_{d} - \psi^{d}_{a} - \delta^{b,d}_{a} \right) \quad \forall a \in R_{d}, \forall b \in R_{t}, \forall d, t \in D, d \neq t
\]

(13)

\[
e^{d}_{a} + p^{a,d} - e^{d}_{b} \leq \nabla \cdot \left( z^{b,d}_{a} + 3 - \psi^{b}_{d} - \psi^{d}_{a} - \delta^{b,d}_{a} \right) \quad \forall a \in R_{d}, \forall b \in R_{t}, \forall d, t \in D, d \neq t
\]

(14)

\[
e^{d}_{a} + p^{a,d} - e^{d}_{b} \leq \nabla \cdot \left( z^{b,d}_{a} + 3 - \psi^{b}_{d} - \psi^{d}_{a} - \delta^{b,d}_{a} \right) \quad \forall a \in R_{d}, \forall b \in R_{t}, \forall d, t \in D, d \neq t
\]

(15)

In objective function (1), the first term aims to maximize the effective protected capacity for end-to-end user data transmission between different node pairs and also to minimize the link protection capacity reserved in the whole network. \( \alpha \) is a weight factor which should be a small value, so that maximizing the FSs for actual data transmission has higher priority; we set \( \alpha = 0.01 \) in this study. \( T_{d} \) is a given parameter to indicate the end-to-end capacity demand between each node pair, while \( \rho_{d} \) is a variable to indicate whether the capacity demand between the node pair can be satisfied subject to limited spectrum resource in each fiber link. \( \rho_{d} \) can be zero if there is no sufficient capacity remained for lightpath established between the node pair. In this sense, \( \sum_{d \in D} \rho_{d} \cdot T_{d} \) is not constant which is to calculate the total successfully satisfied end-to-end capacity demand. Constraint (2) means that a pair of
working and protection lightpaths should be simultaneously established if a protected lightpath demand is successfully served between a pair of nodes. This is to ensure that a lightpath demand is served only if a working lightpath and its corresponding protection lightpath are both successfully established at the same time. Constraint (3) is required by the SBPP protection technique to ensure that there is only one protection lightpath selected for any node pair. Constraint (4) ensures that sufficient spare capacity is reserved on link $j$ such that all the successfully established demands can be supported. Constraints (5) and (6) sum the total number of FSs for each pair of successfully established working and protection lightpaths, which is the sum of the actual required FSs and the extra FSs required for FEC. Constraints (7) and (8) ensure that the ending FS index of each lightpath never exceeds the maximal FS index $C$. Constraints (9) and (10) ensure that any two working lightpaths that share common link(s) do not overlap in their assigned spectra; these two constraints work together. Specifically, if the starting FS index of the working lightpath for node pair $d$ is larger than that of the working lightpath for node pair $t$, then the ending FS index of the first working lightpath must be larger than the ending FS index of the second working lightpath. Based on the above constraints, if the working lightpaths between node pair $t$ and $d$ share a common link $i$, and the starting FS index of the working lightpath for node pair $d$ is larger than that of the working lightpath for node pair $t$, i.e., $e^i_d = 1, x^i_d = 1$, then we get $f^d + w^d > f^t$; otherwise constraints (9) and (10) always hold together. In summary, the two constraints can ensure spectrum non-overlap between different working lightpaths that share common link(s). Similarly, constraints (11)-(13) ensure that a working lightpath and a protection lightpath that share common link(s) should not overlap in their assigned spectra, and constraints (14)-(15) ensure that any two protection lightpaths that share common link(s) whose corresponding working lightpaths share common link(s) should not overlap in their assigned spectra. These two constraints work together and (15) affects spectrum assignment only when two protection lightpaths share a common link and their corresponding working lightpath also share a common link (i.e., $\delta_d^e = 1$). It may be recalled that this is required as according to the definition of SBPP, the two protection lightpaths cannot share any spare capacity on common link(s) in this situation. Specifically, if the starting FS index of the protection lightpath for node pair $d$ is larger than that of the protection lightpath for node pair $t$, then the ending FS index of the first protection lightpath must be larger than the ending FS index of the second protection lightpath. Based on the above constraints, if the protection lightpaths between node pair $t$ and $d$ share a common link $i$, and their corresponding working lightpaths share a common link $j$, and if the starting FS index of the protection lightpath for node pair $d$ is larger than that of the protection lightpath for node pair $t$, i.e., $\delta_d^e = 1, z_d^e = 1$, then we get $e^j_d + p^d > e^j_t$; otherwise, if $\delta_d^e = 0$ which means the two protection lightpaths can share spectrum resources, constraint (15) does not affect spectrum assignment in this situation. In summary, the two constraints can ensure spectrum non-overlap between different protection lightpaths that share common link(s) and whose corresponding working lightpaths also share common link(s).

4.3 Computational complexity

We count the dominant numbers of variables and constraints to evaluate the computational complexity of the ILP model. In the above model, the dominant number of variables is $O(|R| \cdot |D|)$ and the dominant number of constraints is $O(|R| \cdot |D|)$, where $|R|$ is the average number of link-disjoint shortest routes between each pair of nodes and $|D|$ is the number of node pairs in the whole network.
5. SWP-based heuristic algorithm

The RSA problem has been proved to be NP-complete. For large or even reasonably sized networks, the ILP model cannot be solved to obtain an optimal solution within a reasonably short time. Therefore, we also develop an efficient heuristic algorithm for the SWP-based adaptive FEC allocation strategy. For this, we apply the concept of SWP, introduced in [5, 31] to help find routes and assign spectra for the working and protection lightpaths. Only if a pair of eligible working and protection routes can be found in SWPs, can a SBPP lightpath service be established. Thus, the SWP-based adaptive FEC heuristic algorithm can essentially be divided into two steps, i.e., establishing working and protection lightpaths. We next present the SWP-based heuristic algorithm.

Algorithm: SWP-based heuristic algorithm with SBPP-based adaptive FEC

| Input: | A network topology $G$ and a demand list $D$ |
| Output: | The maximal achievable protected capacity for data transmission and the lowest spare capacity required for network protection |

Algorithm 1: Searching for a working route

1. For every demand request in $D$ do
2. Search for the shortest route by Dijkstra’s shortest path algorithm (based on physical distance), calculate OSNR of the shortest route found and determine its corresponding FEC type ($FEC_{int}$); 
3. For the three types of FECs (from $FEC_{int}$ to the third generation of FEC) do
4. Considering overhead of $FEC_{int}$, find total required FSs and create all the available SWPs; 
5. For every SWP (from the lowest to the highest index) do
6. Remove all unavailable spectrum widow (SW) links on each SWP; 
7. Try to find the shortest route on the SWP in hops; 
8. If a route with the least hops is found (as $W_{\text{route}}$) then
9. If OSNR of $W_{\text{route}}$ is larger than the OSNR limit of the current FEC type then
10. Use the corresponding FSs of SWP to establish a lightpath and stop scanning remaining SWPs and other types of FEC; 
11. Else
12. Move to next SWP; 
13. End if 
14. Else 
15. Move to next SWP; 
16. End if 
17. End for 
18. If $W_{\text{route}}$ == Null then
19. Move to next FEC type; 
20. End if 
21. End for 
22. End for 

If the working lightpath is established successfully, then we next try to establish an eligible protection lightpath for it. The algorithm of SBPP for searching for a protection lightpath has two main aspects: (1) judge if SW links are available for the protection lightpath; (2) calculate the appropriate cost of each available SW link which shares FSs.

Under SBPP, there are two conditions for an FS to be available for a protection lightpath: (1) the FS is free; or (2) the FS is sharable for the protection lightpath on the condition that the working lightpaths of all the protection lightpaths that share the FS do not share any common link(s) with the current working lightpath. For the first one, in addition to free FSs, we must ensure that the link containing the FSs is not traversed by the working lightpath in line 4 of algorithm 2. This is used to ensure that the working and protection lightpaths are
link-disjoint for the demand request. For the second condition, we use the approach proposed earlier by us in [31] where the cost $C_{SW}$ of a SW link with $F$ FSs is set by (16) as per the sharing status of each FS by protection lightpaths with (17) giving the cost $C_i$ of $i^{th}$ FS.

$$C_{SW} = \sum_{i=1}^{F} C_i$$  \hspace{1cm} (16)

$$C_i = C_{cost} / (m+1)$$  \hspace{1cm} (17)

In (17), $C_{cost}$ is the original cost of the link using the $i^{th}$ FS and $m$ is the number of protection lightpaths that are sharing the FS. If the FS is free, $m = 0$ and $C_i = C_{cost}$; if it is sharable then the cost is set to be inversely proportional to the number of protection lightpaths that share that FS. The logic followed here is that it would be more efficient to assign a smaller cost to an FS if it is shared by more protection lightpaths. The RSA algorithm for a protection lightpath using these concepts is given next.

---

**Algorithm 2: Searching for a protection route**

1. **For** every demand request $d$ in $D$ **do**
   
   Search for the second shortest route that is link-disjoint from the first shortest route by K-disjoint shortest path algorithm (based on physical distance), calculate OSNR for the found route and find its corresponding FEC type ($FEC_{int}$);

2. **For** the three types of FECs (from $FEC_{int}$ to the third generation of $FEC$) **do**
   
   Considering overhead of $FEC_{int}$, find total required FSs and create all the available SWPs;

3. Remove all links traveled by the working lightpath from each SWP;

4. Remove all links from each of the SWPs if corresponding SWs are not available, i.e., not all $F$ continuous FSs are free or sharable, where $F$ is the total needed FSs (including FEC overhead) of the protection lightpath of $d$;

5. **For** every SWP (as $Current\_SWP$) (from the lowest to the highest index) **do**

   Calculate cost $C_{sw}$ of each available SW link on $Current\_SWP$ using (16) and (17);

   Try to find the shortest route on $Current\_SWP$ with the least cost;

   **If** a route with the least cost is found (as $P\_route$) **then**

   **If** OSNR of $P\_route$ is larger than OSNR limit of the current FEC type **then**

   Use the corresponding FSs of $Current\_SWP$ to establish the lightpath and stop scanning remaining SWPs and other types of FEC;

   Else

   Move to next SWP;

   **End if**

   Else

   Move to next SWP;

   **End if**

   **End for**

   **If** $P\_route == Null$ **then**

   Move to next FEC type;

   **End if**

   **End for**

---

It can be seen that the algorithmic steps of algorithms 1 and 2 are similar except for the following two aspects. Firstly, the conditions of removing an SW link from its corresponding SWP are: (1) its physical link is traversed by the working lightpath; (2) any one of the contained FSs is occupied and not shareable. Secondly, for the protection lightpath, the cost
of each link is calculated by (16) and (17), not simply as the hop number in the way that it is
done for a working lightpath.

If algorithm 2 is unsuccessful in obtaining a protection route for \( d \), then \( d \) is blocked;
otherwise, a protection route is obtained and the SBPP-protected service can be established
successfully. We will assign the spectra of the corresponding SWPs to the working and
protection lightpaths of request \( d \), respectively. The way of spectrum assignment is given
next.

Algorithm 3: Assigning spectra

1. For each link traversed by working lightpath of \( d \) do
2.   For each FS (from firstindex to endindex) on the found SWP do
3.     Add \( d \) to occupiedrequestlist of the FS;
4.   End for
5. End for
6. For each link traversed by the protection lightpath of \( d \) do
7.   For each FS (from firstindex to endindex) on the found SWP do
8.     Add \( d \) to occupiedrequestlist of the FS;
9.   End for
10. End for

In algorithm 3, we define an array list named occupiedrequestlist to store the established
requests that use the FS. From lines 1 to 5, the algorithm tries to assign spectrum for the
working lightpath, which assigns frequency slots indexed from firstindex to endindex to each
link traversed by the working route stored to W_route. Similarly, from lines 6 to 10, the
algorithm tries to assign spectrum for the protection lightpath.

As described in [31], the SWP-based algorithm does have important differences with the
traditional waveplane-based algorithm for a WDM network. The number of waveplanes is
fixed for a given WDM network with a certain number of wavelengths. In contrast, the
number of SWPs is not fixed and will depend on the required bandwidth plus required FEC
overhead between each node pair and the chosen route for lightpath establishment. For an
elastic optical network with \( M \) FSs per fiber, there are \( M - x + 1 \) SWPs for a lightpath with
\( x \) FSs. Note that \( x \) is different for different node pairs, different lightpath routes, and FEC
types. Secondly, for the protection lightpath, each shared FS has different costs, which makes
the cost of each SW link different from that of each shared wavelength in a WDM network.
Thus, the SWP-based algorithm is more complicated and should be considered more
carefully.

5.1 Computational complexity

The SWP-based adaptive FEC heuristic algorithm includes the steps of searching for working
and protection lightpaths. The maximum complexity of algorithm 1 is

\[
O \left( T \cdot (W - |F| + 1) \cdot \left( |F| \cdot |E| + |V|^2 \right) \right)
\]

where \( T \) is the number of FEC types, \( |F| \) is the

number of FSs required by a demand, \( |E| \) is the number of network links, \( |V| \) is the number

of network nodes, and \( W \) is the total number of FSs in each fiber link. \( W - |F| + 1 \) is the

number of SWPs for a lightpath demand. We note that \( O (|V|^2) \) is the complexity of the

shortest route searching algorithm and \( O (|F| \cdot |E|) \) is the complexity for finding all

unavailable links for working route searching. For the protection lightpath, there is a similar

computational complexity to that of the working lightpath. The link cost calculation in line 7

is an additional step to algorithm 1, whose corresponding complexity is \( O (|F| \cdot |E|) \). Thus,

the overall computational complexity of the whole algorithm is

\[
O \left( T \cdot (W - |F| + 1) \cdot (2 \cdot |F| \cdot |E| + |V|^2) \right)
\]

The complexity of lines 1-5 in algorithm 3
is $O(\varphi |F|)$, where $\varphi$ is the number of links traversed by working lightpath. Similarly, the complexity of lines 6-10 in algorithm 3 is $O(\phi |F|)$, where $\phi$ is the number of links traversed by the protection lightpath.

6. Performance comparison

To evaluate the performance of the RSA approaches for a SBPP-based EON with adaptive FEC allocation, we performed a set of simulation studies based on two test networks: (a) a 6-node, 9-link (n6s9) network and (b) the 14-node, 21-link NSFNET network as shown in Fig. 2. The number shown near each link is the physical distance of the link in units of km. Table 2 shows the detailed topological information of the two test networks. Figure 2(c) shows the distribution of the first and second shortest paths that are suitable for the different types of FECs according to their individual OSNRs. We assume that there are a maximum of 140 FSs available in each fiber link in the n6s9 network, and 320 FSs available in the NSFNET network. Table 2 also shows the number of capacity demand requests (i.e., node pairs) in each demand matrix. For each demand request, we assume that the number of FSs required is random within a range of $[X-5, X+5]$, where $X$ is the average number of FSs required by each lightpath demand and the bandwidth of each FS is 12.5 GHz. However, FS is just a capacity unit, which can actually be other bandwidth if different FS grids are used, e.g., 6.25 GHz. $X$ ranges from 10 to 30 FSs, which maximally corresponds to 375 GHz if each FS has 12.5-GHz bandwidth. It is practical to maximally assume a super-channel to have a 375-GHz bandwidth as today 400-Gb/s (corresponding to 400 GHz if the BPSK modulation format is employed) channels are under test by carriers and 1-Tb/s (corresponding to 500 GHz if the QPSK modulation format is employed) channels have been experimentally demonstrated. In the ILP model, each node pair has a pre-calculated route set that contains a maximum of three candidate routes found by the $k$-shortest path searching algorithm. It should be noted that each route added to the set must have an OSNR larger than the lowest OSNR limit (i.e., 9.1 dB) required by the most advanced FEC type (see Table 1); otherwise, it would not be possible to transparently establish a lightpath which would satisfy the required BER on that route. As an extreme case, if there is a node pair whose route is long enough so that its OSNR is even lower than the lowest OSNR limit, then a signal regenerator should be added in the middle of the route. In this study, all the routes between each pair of nodes have OSNRs larger than the lowest OSNR limit even for the larger NSFNET network. We decided the most efficient FEC type for each of the routes based on the performance of each FEC type shown in Table 1 and LDPC (4161, 3431, 0.825) FEC type is employed for all the lightpaths when the network is operated under the uniform FEC allocation strategy.

A commercial software AMPL/Gurobi (version 5.0.0) [32] that was run on a 64-bit server with 2.4-GHz CPU and 8-G memory was employed to solve the ILP model of n6s9. The MIPGAP for the ILP solutions was set to be 0.01%. For n6s9, the ILP model can get an optimal solution within a reasonable short time. Among all the test cases (i.e., from $X=10$ to $X=30$ FSs), the longest solution time is shorter than 128 seconds. However, we could not obtain the ILP result for NSFNET within a reasonable short time due to its large size. Thus,
we have only employed the heuristic algorithm to find sub-optimal solutions. The execution time of the heuristic algorithm is within 2 seconds for n6s9 and within 20 seconds for NSFNET for all the test cases.

We have used Java to program the heuristic approaches: (1) fixed (or uniform) FEC allocation strategy with fixed shortest and second shortest path routing for the working and protection lightpaths for request \(d\) and the first-fit FS assignment (denoted as “FF_SP” in legend), (2) adaptive FEC allocation strategy with fixed shortest and second shortest paths routing for working and protection lightpaths for request \(d\) (denoted as “AF_SP” in legend), (3) the SWP heuristic algorithm with fixed and adaptive FEC scheme (denoted as “FF_SWP” and “AF_SWP” in legend, respectively), and (4) adaptive and fixed FEC scheme based on the ILP optimization model (denoted as “AF_ILP” and “FF_ILP” in legend, respectively). The reason for considering the first two heuristics is to highlight the efficiency of the SWP algorithm.

### Table 2. Topological Information of Two Test Networks

<table>
<thead>
<tr>
<th>Net</th>
<th>#Nodes</th>
<th>#Demands</th>
<th>#Links</th>
<th>Avg. link length (km)</th>
<th>Avg. shortest path length (km)</th>
<th>Avg. second shortest path length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n6s9</td>
<td>6</td>
<td>15</td>
<td>9</td>
<td>1616</td>
<td>2253</td>
<td>3582</td>
</tr>
<tr>
<td>NSFNET</td>
<td>14</td>
<td>91</td>
<td>21</td>
<td>1321</td>
<td>2825</td>
<td>4664</td>
</tr>
</tbody>
</table>

#### 6.1 Carried protected capacity

We evaluate the performance of the SWP-based and SP-based FEC assignment schemes with SBPP network protection. We first evaluate from the perspective of effective protected capacity (which is defined as the sum of FSs for actual end-to-end user data transmission, excluding the extra FEC overhead slots and the reserved FSs for protection lightpaths, i.e., as \(\sum_{d \in D} \rho_d \cdot T_{d}\).

![Fig. 3. Effective protected transmission capacity of different approaches.](image)

Figure 3 shows the effective protected transmission capacity with SBPP protection for the two test networks. We can see that for all the approaches, the adaptive FEC allocation strategy can always provide higher effective protected transmission capacity than the fixed FEC allocation strategy given the same limited spectrum resource in each test network. This is because the adaptive FEC allocation strategy uses the most efficient FEC type according to the actual OSNR of each lightpath rather than the most advanced FEC type and therefore needs fewer FSs for the FEC overhead than the fixed FEC. It may also be noted that the SWP-based strategy can provide higher effective protected transmission capacity than the SP-based strategy. This is reasonable since the SWP-based approach considers alternate routes for the working and protection lightpaths, respectively. This provides more opportunities to implement optimization for maximizing the effective protected transmission capacity.
contrast, the working and protection lightpaths are pre-defined as the shortest path and the second shortest path, respectively, for the SP approach.

It was not feasible to use the ILP approach for the NSFNET network because of the computational complexity involved. For the simpler n6s9 network, the ILP approach could be implemented and the ILP results have been included in Fig. 3(a). As expected, we can observe that the ILP approach, being optimal, performs better than the proposed SWP-based heuristic approach. Though the SWP-based heuristic with adaptive FEC (i.e., AF_SWP) gives results which are quite closer to the optimal results than the SP-based approach, but it may be possible to find even better heuristic approaches which would give results closer to those obtained through the ILPs.

### 6.2 Spare capacity redundancy

We have also evaluated the spare capacity required to be reserved for network protection for the different approaches. Figure 4 shows the results of spare capacity redundancy, which is defined as the ratio of the sum of total protection capacity and total FEC overhead of working lightpaths to the total effective transmission capacity on all links in the whole network, i.e.,

\[
\frac{\sum_{i=1}^{N} S_i + \sum_{i=1}^{N} O_i}{\sum_{i=1}^{N} W_i}.
\]

Here, \( S_i \) is the total number of occupied FSs on span \( i \) by protection lightpaths, which is the sum of the protection FSs used for actual user data transmission and the FSs used for protection lightpath FEC overheads. \( O_i = \sum_{d \in D} \eta_{d} \cdot \rho_{d} \cdot K_{d} \), which is defined as the total FEC overheads (in units of FSs) of working lightpaths on span \( i \). \( W_i = \sum_{d \in D} \eta_{d} \cdot \rho_{d} \cdot T_{d} \), which is defined as the total number of FSs on span \( i \) used by working lightpaths excluding FSs used as the FEC overheads of the working lightpaths (i.e., excluding \( O_i \)).

Note that this spare capacity redundancy is novel, different from the traditional definition that does not consider the redundancy of FEC overhead. For both the test networks, we find that the fixed FEC allocation schemes show higher spare capacity redundancies than the corresponding adaptive FEC allocation schemes. This is because the adaptive FEC allocation strategy uses the most efficient FEC type according to the actual OSNR of each lightpath rather than the most advanced FEC type as done for the fixed case. This would save more spectral resource for actual user data transmission. In contrast, the fixed FEC scheme would need more spare capacity for its FEC overhead. For the n6s9 network for which the ILP model could be used, we find that the ILP model shows even lower spare capacity redundancy than the SWP-based heuristic algorithms. This is expected as the ILP model also considers minimizing the total protection capacity as its second optimization objective.

![Fig. 4. Spare capacity redundancy of different schemes.](attachment://fig4.png)

### 6.3 Average FEC overhead per lightpath

In Fig. 5, we have also shown the average FEC overhead required by each established lightpath (either working or protection lightpath) under different FEC assignment approaches.
“W_AF_SWP” and “P_AF_SWP” indicate the respective average FEC overheads for the working and protection lightpaths with the SWP-based adaptive FEC allocation strategy. Similarly, “W_AF_SP” and “P_AF_SP” indicate the respective average FEC overheads for the working and protection lightpaths with the SP-based adaptive FEC allocation strategy, and “W_AF_ILP” and “P_AF_ILP” indicate the respective average FEC overheads for the working and protection lightpaths with the adaptive FEC allocation based on the ILP optimization model. Since the fixed FEC strategy always assigns the best FEC type for all the lightpaths, its average overhead is the highest. Moreover, for the same network, the protection lightpath has higher average overhead than the working lightpath because the former would have a longer path than its corresponding working lightpath and need a better FEC type to satisfy the higher OSNR of the longer route.

All the three adaptive assignment approaches have much lower average overheads compared to the fixed FEC strategy because of their inherent flexibility in assigning different FEC types. In addition, as shown in Fig. 5, with the proposed adaptive FEC assignment, the ILP model and the proposed SWP-based scheme have an average FEC overhead close to that of the SP-based scheme even though the former can provide higher effective protected transmission capacity than the latter. This reaffirms our claim that the proposed SWP-based adaptive FEC allocation strategy would be more spectrally efficient in FEC type assignment.

6.4 Distribution of FEC types

In this section, we estimate the distributions of the different FEC types used for lightpath establishment. Figure 6 shows the percentages of different FEC types employed for the working and protection lightpaths. In Figs. 6(a) and 6(c), we can see that for working lightpaths, the percentage of FEC type RS (255, 239) is the highest, that of LDPC (4161, 3431, 0.825) is the lowest, and that of RS (255, 239) + BCH (1023, 693) is in between. This is in line with the lightpath distance distribution in the two networks. In addition, as shown in Fig. 2(c), overall NSFNET has a lower percentage of the first shortest paths (i.e., corresponding to working lightpaths) that fall in the transparent reach range of RS (255, 239) than n6s9. Thus, we can see that overall for the SP scheme NSFNET has a lower percentage of RS (255, 239) for the traffic demand cases of 10, 15, 25, and 30 FSs. For the case of 20 FSs, NSFNET seems to have a little bit higher (3%) percentage of RS (255, 239) than n6s9. This is attributed to the randomness of the traffic demand. In the section of test condition, we assumed that the number of FSs per node pair is randomly generated surrounding an average of 20 FSs, i.e., within a range of [X-5, X + 5] with X = 20. The randomness may cause some situation that seems abnormal in the percentage distribution of FEC types. Overall n6s9 shows to use more RS (255, 239) on average than NSFNET. The result curves well reflect this trend.

For the protection lightpaths, as shown in Figs. 6(b) and 6(d), the percentage of FEC type RS (255, 239) + BCH (1023, 963) is the highest in the n6s9 network, while the percentage of FEC type LDPC (4161, 3431, 0.825) becomes higher in the NSFNET network. This is
probably because of different network sizes of the two test networks. In the n6s9 network, the
distances of most protection lightpaths are in the range of the transparent reach of RS (255, 239) + BCH (1023, 963), while in the NSFNET network, more protection lightpaths are in the range of the transparent reach of LDPC (4161, 3431, 0.825). NSFNET shows to use a higher percentage of RS (255, 239) than n6s9. This is because in Fig. 2(c) we see that NSFNET has a higher percentage of the second shortest paths (i.e., corresponding to protection lightpaths) that fall in the transparent reach range of RS (255, 239) than n6s9. This explains for the SP scheme why NSFNET has higher percentage of RS (255, 239) than n6s9 in Figs. 6(b) and 6(d).

In addition, comparing the FEC type distributions of the working and protection lightpaths, we find that the working lightpaths use more lower-level FEC types. This is because a working lightpath is in general shorter than its corresponding protection lightpath, and therefore a lower level FEC type would suffice for the working lightpath.

7. Conclusion

This paper applies an adaptive FEC allocation strategy along with the SBPP protection technique to jointly reduce the FEC overhead and enhance network survivability for an elastic optical network. To study the performance of the proposed strategy, as compared with the standard shortest-path algorithm, we develop an ILP based optimization model and a SWP-based heuristic algorithm, both to maximize the effective protected transmission capacity and to minimize the spare capacity required for network protection. Results show that compared with the traditional fixed FEC allocation strategy, substantial savings in the FEC overhead can be achieved by the SBPP-based adaptive FEC allocation strategy which would therefore significantly augment the overall effective transmission capacity of the network. Our performance studies also show that the distribution of the FEC types used is closely related to the network size and that the working lightpaths generally use lower-level FEC types with lower FEC overhead than the protection lightpaths. We observe that the ILP model and the proposed SWP-based FEC allocation scheme have similar average FEC overheads even though they can provide higher effective protected transmission capacity than the SP-based approach. This further confirms our expectation that the proposed SWP-based adaptive scheme would be spectrum efficient in FEC type assignment.
Acknowledgments

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