Adaptive FEC Selection for Lightpaths in Elastic Optical Networks

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Abstract: We propose a new approach to adaptively select FEC types for lightpaths in elastic optical networks. An ILP model and a spectrum-window-based heuristic algorithm are developed to analyze its performance. The proposed FEC selection scheme can achieve good performance with low FEC overhead. ©2014 Optical Society of America

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1. Introduction

Optical transmission systems are being increasingly used for higher data rates over longer distances, but would need Forward Error Correction (FEC) techniques to compensate for OSNR degradation. For a particular FEC type, Net Coding Gain (NCG) is a common performance parameter to measure the efficiency of the coding technique. Another significant parameter for FEC is the coding overhead (OH), defined as the ratio of the number of redundant bits to the number of information bits. Three FEC types commonly applied at present are block codes, concatenated codes, and soft-decision decoding as per ITU-T G.975 [1]. Future fiber optical transmission systems based on the CO-OFDM technology can operate as an elastic optical network, in which multiple contiguous frequency slots (FSs) are allocated to each lightpath. With FEC, in addition to the FSs actually required for data transmission, extra FSs should be allocated for the FEC overhead. Traditional methods for FEC selection tend to simply employ an FEC type with the highest NCG and lowest OSNR limit for all the lightpaths. FEC with the highest NCG (and the highest overhead) would be used even for lightpaths with good OSNRs, which therefore would use more FSs than actually needed. Given the limited spectrum resource on each fiber, it is meaningful to avoid this wastage for better spectrum utilization, and moreover, simpler FECs would also be easier and cheaper to implement. In this paper, we apply the adaptive FEC selection strategy that was developed in [2] for the WDM networks to the elastic optical networks so as to reduce the extra required spectra by FEC overhead. We develop an ILP model and an efficient spectrum-window-based heuristic algorithm to analyze the performance of the approach.

2. Adaptive FEC Selection Strategy

We use an example in Fig. 1 to explain the concept of adaptive FEC selection in elastic optical networks. For lightpath establishment, we choose three FEC types as the candidate FEC type set from all the three generation of FECs, i.e., RS(255, 239) [3], RS(255, 239)+BCH(1023, 963) [4], and LDPC(4161, 3431, 0.825) [5]. Their detailed performance information is shown in Table I. Three lightpaths 0-1, 0-3, 0-4 are to be established. Since among all the lightpaths, the one between node pair (0-3) has the lowest OSNR (i.e., OSNR3 = 10dB), the traditional FEC selection strategy would choose FEC type 3 with the highest NCG and the lowest OSNR for all the lightpaths. FEC with the highest NCG (and the highest overhead) would be used even for lightpaths with good OSNRs, which therefore would use more FSs than actually needed.

Given the limited spectrum resource on each fiber, it is meaningful to avoid this wastage for better spectrum utilization, and moreover, simpler FECs would also be easier and cheaper to implement. In this paper, we apply the adaptive FEC selection strategy that was developed in [2] for the WDM networks to the elastic optical networks so as to reduce the extra required spectra by FEC overhead. We develop an ILP model and an efficient spectrum-window-based heuristic algorithm to analyze the performance of the approach.

3. ILP Optimization Model

A path-arc Integer Linear Programming (ILP) model is developed to maximally satisfy the traffic demands and meanwhile minimize the total FEC overhead by optimally choosing FEC types for each lightpath, under the...
assumption of a limited number of FSs on each fiber link and the constraint of lightpath spectrum continuity. We first present the notations of the model as follows: \( L \) is the set of links. \( D \) is the set of node pairs. \( R^d \) is the set of candidate routes between node pair \( d \). \( T_d \) is the number of required FSs between node pair \( d \). \( T_{d}^{a} \) is the extra required FSs on path \( r \) of node pair \( d \) due to FEC overhead. \( \sigma_i^{d_1r_1} \) if link \( i \) is traversed by path \( r \) of node pair \( d \); 0, otherwise. \( C \) is the maximum FS index used in the network. \( \alpha \) is a small value. \( F \) is a large value. \( T_{tot}^d \) is the total number of FSs required for establishing a lightpath between node pair \( d \). \( r_d^i = 1 \) if path \( r \) of node pair \( d \) is used for lightpath establishment; 0, otherwise. \( S_d \) and \( E_d \) are integer variables denoting the starting and ending FS indexes of the lightpath between node pair \( d \). \( \delta_{d1}^{d2} = 1 \) if \( E_{d1} < S_{d2} \) with \( d1 \neq d2 \); 0, otherwise.

**Objective:** Minimize \( \alpha \sum_{d \in D} \sum_{r \in R^d} r_d^i \cdot T_r^d \cdot \rho_d^i - \sum_{d \in D} \sum_{r \in R^d} r_d^i \cdot T_r^d \). where the second term is to maximize total served demands and the first term is to minimize total required FEC overhead. By setting a small value for weight factor \( \alpha \), the second term (i.e., maximizing total served demands) becomes the first priority.

**Subject to:**
\[
\sum_{r \in R^d} r_d^i \cdot T_r^d \leq 1 \quad \forall d \in D \quad (1)
\]
\[
E_d - T_{tot}^d - S_d + 1 \leq F \cdot (1 - \sum_{r \in R^d} r_d^i) \forall d \in D \quad (2)
\]
\[
C \geq E_d \quad \forall d \in D \quad (3)
\]
\[
C \geq \sum_{d \in D} \sum_{r \in R^d} \delta_{d1}^{d2} \cdot T_{tot}^d \quad \forall i \in L \quad (4)
\]
\[
E_{d2} - S_{d1} \leq F \cdot (\delta_{d1}^{d2} + \delta_{d2}^{d3} - 2) \cdot r_d^i \cdot (T_r^d - \sum_{r \in R^d} r_d^i \cdot \sigma_i^{d1r_1} - \sum_{r \in R^d} r_d^i \cdot \sigma_i^{d2r_2}) - 1 \forall i \in L, \forall d1 \in D, \forall d2 \in D, d1 \neq d2 \quad (5)
\]

Constraint (5) ensures that the maximal FS index used \( C \) is always larger than the starting FS index of each lightpath. Constraints (6) and (7) are redundant ones helping reduce the feasible solution region of the ILP model. Constraints (8) and (9) ensure any two lightpaths that share common link(s) not to overlap in their assigned spectra.

### 4. Spectrum-Window-Based Heuristic Algorithm

Though the ILP model guarantees optimal results, its computational complexity makes it infeasible for all but small networks. Extending the spectrum-window-based algorithm in [6], we develop a new heuristic Adaptive FEC Selection-based Spectrum Window (AFS-SW) algorithm to find an efficient solution for the problem. In Fig. 3, we use a 3-node 3-link network to illustrate the concept of spectrum window where each link has 12 FSs and three contiguous idle FSs are required for each lightpath. We first generate the spectrum-availability virtual topologies which are referred to as spectrum window planes (SWPs). Specifically, on each fiber link, if three contiguous FSs are idle, then this link is added to a spectrum window plane. The links with the same FS indexes are put in the same spectrum window plane. In this example, four spectrum window planes are created with at least one virtual link included in each of the planes. To establish a 3-FS lightpath between a pair of nodes, we search each of the spectrum window planes to find the best one. Fig. 4 shows a general flowchart for the AFS-SW algorithm. The key idea is to apply the SWP concept to search each possible route under different generations of FECs and to choose the shortest route with the lowest overhead. Due to the page limit, readers please see the detailed steps in Fig. 4.

### 5. Results and Performance Analyses

We consider two test networks, a 6-node 9-link network and the 24-node 43-link US backbone network (USNET). We assume that in total, 80 FSs per fiber are available in the 6-node network and 400 in USNET. The deployment of optical amplifiers on each link and the approach for calculating OSNR of each lightpath are as in [2]. Between each
node pair, the required FSs number is generated randomly within a range of \([X-5, X+5]\), where \(X\) is the average number of FSs or demand intensity. Lightpath spectrum continuity is assumed and only one lightpath is allowed between each node pair. For the ILP model, we find up to three candidate routes between each node pair and use them as the candidate route set if their calculated OSNRs are larger than the lowest OSNR limit (i.e., 9.1 dB). Based on the calculated OSNR of a lightpath, the most efficient FEC type is chosen according to Table I. Using the commercial software AMPL/Gurobi, we solve the ILP model for the 6-node network. We also run the AFS-SW algorithm for both of the test networks. In addition, for comparison, we present the results achieved by the approach simply based on fixed shortest path routing and first-fit FS assignment.

Fig. 5: Number of satisfied demands

Figs. 5(a), 6(a), 7(a) show the performance of the FEC selection schemes in the 6-node network. In Fig. 5(a), it is found that all the adaptive FEC schemes can serve more demands than the fixed FEC scheme (i.e., “Fixed-FEC” in legend). For the adaptive FEC schemes themselves, it is found that our ILP model (“ILP”) and AFS-SW algorithm (“AFS-SW”) perform similarly and do much better than the simple shortest-path scheme (“Shortest-path”). Fig. 6(a) shows the percentage distribution of different FEC types used. We can see that the percentage of FEC type RS(255, 239) is the highest and that of LDPC(4161, 3431, 0.825) is the lowest. In addition, the number of lightpaths with LDPC(4161, 3431, 0.825) are observed to decrease with the increase of average FSs number of each demand. This is because subject to the limited FS resource on each fiber, a larger average FSs number makes the network tend to serve more demands along shorter routes so as to maximize the total served demands. Fig. 7(a) compares the average FEC overhead per lightpath between the fixed FEC and adaptive FEC schemes. We can see that the fixed FEC scheme shows a much higher average lightpath overhead than the other three adaptive schemes. In addition, the average lightpath overheads of all the adaptive schemes are found to be very close, though the ILP model and the AFS-SW algorithm can serve more lightpath demands. We also show the results for the larger USNET network in Figs. 5(b), 6(b), 7(b), where the results of the ILP model are however not provided because the network is too large for AMPL/Gurobi to find optimal solutions within a reasonable time. In Fig. 5(b), we can see that the number of satisfied demands of the AFS-SW algorithm is larger than that of the shortest-path scheme. Similarly, the percentage of FEC type RS(255, 239) is the highest and the LDPC(4161, 3431, 0.825) is the lowest as shown in Fig. 6(b). In addition, in Fig. 7(b), again we see that both of the adaptive schemes show far lower average overhead than the fixed-FEC scheme, and our AFS-SW algorithm performs very closely to the shortest-path adaptive scheme though the former can serve more lightpath demands.

6. Conclusion

In order to reduce the overhead cost and improve spectrum utilization for elastic optical networks, we developed an adaptive FEC selection scheme for lightpaths. To analyze the performance of the proposed approach, we developed an ILP model and a spectrum-window-based heuristic algorithm to maximize the total satisfied demands while minimizing the FEC average overhead. Compared with the fixed-FEC scheme, a large amount total overhead (extra FSs) can be saved by the adaptive FEC scheme. Also, we find that our AFS-SW algorithm performs closely to the ILP model in terms of the total satisfied demands and average FEC overhead.

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