Optical Switching and Networking 14 (2014) 241–249

Contents lists available at ScienceDirect

Optical Switching and Networking

journal homepage: www.elsevier.com/locate/osn

Adaptive FEC-based lightpath routing and wavelength assignment in WDM optical networks ☆

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ARTICLE INFO

Article history:
Received 6 March 2014
Received in revised form
30 April 2014
Accepted 13 May 2014
Available online 5 June 2014

Keywords:
Adaptive forward error correction (FEC)
Optical signal to noise ratio (OSNR)
Shuffled demand sequences
Waveplane-based heuristic algorithm

ABSTRACT

Forward error correction (FEC) has been widely used in optical communication systems to compensate for the degradation of the received optical signal to noise ratio (OSNR). Current optical networks tend to use the same type of FEC for all the lightpaths even though lightpaths with higher OSNRs can be established by FECs with lower overhead. This paper proposes an adaptive approach to choose the most efficient FECs for different lightpaths based on their individual OSNRs. An Integer Linear Programming (ILP) model and a simple waveplane-based heuristic algorithm considering shuffled lightpath demand sequences are developed to tackle the routing and wavelength assignment (RWA) problem. The simulation results indicate that compared to the non-adaptive case, using the proposed adaptive FEC selection scheme can significantly reduce the required FEC overhead. Apart from being far more tractable, the proposed heuristic approach performs almost as well as the ILP model.

1. Introduction

With the increase of traffic demand in backbone networks over the past few years, optical transmission systems are moving towards higher data rates over longer distances. However, in these systems, the physical-layer impairments such as fiber dispersion, nonlinear effects, channel noise, and other factors can significantly degrade the OSNRs of optical signals and thus impose a serious restriction on the transmission data rates and distances. The forward error correction (FEC) coding technique is considered as an effective way to compensate for the OSNR degradation. This technique has advantages of low hardware investment cost and high error-correction performance, and therefore has been widely used in fiber-optics transmission systems.

The forward error correction techniques can be classified into three generations [2]. The first generation of FEC was based on the hard decision decoding technique that uses block codes, of which a typical example is the RS (255, 239) code with a Net Coding Gain (NCG) (@BER$=10^{-13}$) of 5.8 dB. The second generation of FEC mainly focused on the concatenated codes, e.g., RS(239, 223)+RS (255, 239) and RS+BCH with an NCG (@10^{-13}) of 7–9 dB. The third generation of FEC is based on more powerful soft-decision codes such as low-density parity-check code (LDPC) and Block Turbo codes. They have typical NCGs (@10^{-13}) greater than 10 dB. In addition, the FEC coding techniques can be divided into the categories of in-band and out-band coding. The in-band coding technique uses the overhead bytes of a frame to store the FEC

☆ Part of the paper was presented in ACP 2013 [1]. This work was jointly supported by the National 863 Plans Project of China (2012AA011302), National Natural Science Foundation of China (NSFC) (61172057, 61322109), Research Fund for the Doctoral Program of Higher Education of China (20113201110005), and Natural Science Foundation of Jiangsu Province (BK2012179, BK20130003).

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http://dx.doi.org/10.1016/j.osn.2014.05.021
1573-4277/

redundant bits. The SONET/SDH frame is a typical example of this type of in-band coding [3]. However, the limited overhead bytes in a frame (e.g., a SONET/SDH frame) restrict the highest coding performance of FEC. In contrast, as recommended in ITU-T G.975 [4] and G.709 [5], the out-band coding technique allows us to increase the line data rate using an extra overhead for FEC encoding, which can therefore maximize the performance benefit of FEC coding by increasing the number of redundant bits.

Much effort has been made for studying FEC with different error correcting capabilities [6–13]. The experiment performed by Grover in 1988 was recognized as one of the first experimental FEC implementation in optical systems. By using the Hamming code, the coding gain of this FEC was only 2.5 dB (@10^{-13}) [6]. As the wavelength division multiplexing (WDM) technique matured, researchers focused on constructing more complex codes. The most representative ones are Turbo and LDPC codes [7–9] where the LDPC codes can even come very close to the Shannon limit (i.e., within 0.04 dB) [9]. Along with these more powerful FEC codes, related techniques such as interleaving, iterative decoding and soft-decision decoding based on multiple thresholds are employed to further improve the error correction performance [10,11]. In [12,13], the authors also present the future development trends in FECs so as to cater to further increases in transmission impairments.

While these advances take the FEC coding techniques closer to the Shannon coding limit, there is a clear tradeoff between improved FEC coding performance and the growing coding overhead (OH); the increasing coding overhead shows up as additional line rate for the optical channel. The Net Coding Gain (NCG) is a typical measure for the coding efficiency of any particular type of FEC. Long-haul optical transmission systems must employ FEC types with higher NCGs in order to ensure a satisfactory BER with a lower OSNR requirement.

The traditional FEC selection approach often chooses the best FEC (i.e., with the highest NCG such as the third generation of FEC) to cater for the lightpaths with the poorest OSNR in the whole network. This approach unnecessarily increases the overall network FEC coding overhead and therefore reduces network transmission capacity efficiency for lightpaths with higher OSNRs. Moreover, it also increases the network hardware cost because lightpaths tend to be over-engineered with more expensive FECs.

To tackle the disadvantage of the uniform FEC selection strategy, this paper proposes an adaptive FEC selection approach for the optical channels. This approach chooses the most efficient FEC based on the actual OSNR of a lightpath. In the current stage, it is technically mature to implement the adaptive FEC selection strategy for *static* lightpath routing and optical channel establishment. With the further development of networking techniques such as software-defined optical networks (SDONs) [14–16] and real-time optical OSNR estimation [17], it is also feasible to implement the adaptive FEC selection in an *online* fashion. The software-defined optical networks which have been considered as a promising solution for a more flexible optical network can support the adaptive FEC selection approach. In such a type of network, optical transponders are controllable in many dimensions so that the related parameters such as the modulation formats and the types of FECs used by optical channels can be adjusted on demand by the control plane. In addition, with the support of optical performance monitoring, it is possible to estimate the OSNR of each lightpath online, which also provides the feasibility to choose different FEC types based on the actual OSNR of an optical channel. With the FEC selection for each optical channel decided in this fashion, we investigate the Routing and Wavelength Assignment (RWA) issues which would be important for the optical networks.

Though there have been many studies on the RWA problem [18–24], this paper, for the first time, incorporates the FEC selection issue in lightpath routing and wavelength assignment. We propose an ILP optimization model and an efficient waveplane-based heuristic algorithm for the RWA problem which takes an adaptive FEC strategy into account. We evaluate the performance through simulations and find that compared to the non-adaptive scheme, using the proposed adaptive FEC selection approach can significantly reduce the required FEC overhead of lightpaths.

This paper has focused on the WDM network because it is the most dominant in today's transport networks. The adaptive FEC selection strategy uses the most efficient FEC type for each WDM optical channel, which can simplify the FEC coding algorithm, shorten the coding delay, as well as minimize the FEC overhead. As another study case, we can also apply this strategy to the elastic optical network.

The rest of the paper is organized as follows. In Section 2, we introduce the adaptive FEC selection strategy. In Section 3, we explain in detail how to evaluate the OSNR of a lightpath. To solve the FEC-based RWA problem, we develop an ILP model and a waveplane-based heuristic algorithm in Sections 4 and 5, respectively. In Section 6, we present and analyze the simulation results. Section 7 concludes the paper.

2. Adaptive FEC selection

In this section, we explain the proposed adaptive FEC selection strategy. For a 100 Gbps optical channel, we

Table 1
Information on three FEC types.

FEC Type	Overhead (%)	Data rate (Gbps)	NCG	CG (dB)	Q limit (dB)	OSNR limit (dB)
RS(255, 239)	6.69	106.69	5.8 dB@10^{-13}	6.08	11.2	14.5
RS(255, 239)/ BCH(1023, 963)	13.34	113.34	7.3 dB@10^{-12}	7.92	9.0	12.6
LDPC(4161, 3431, 0.825)	21.2	121.2	11.27 dB@10^{-13}	12.1	5.2	9.1