Optical Fiber Technology 40 (2018) 93–100

Contents lists available at ScienceDirect

Optical Fiber Technology

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

On optimal designs of transparent WDM networks with 1 + 1 protection leveraged by all-optical XOR network coding schemes

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ARTICLE INFO

Keywords:
Transparent WDM networks
1 + 1 dedicated protection
All-optical XOR
Network coding
Integer linear programming
Routing and wavelength assignment

ABSTRACT

Network coding techniques are seen as the new dimension to improve the network performances thanks to the capability of utilizing network resources more efficiently. Indeed, the application of network coding to the realm of failure recovery in optical networks has been marking a major departure from traditional protection schemes as it could potentially achieve both rapid recovery and capacity improvement, challenging the prevailing wisdom of trading capacity efficiency for speed recovery and vice versa. In this context, the maturing of all-optical XOR technologies appears as a good match to the necessity of a more efficient protection in transparent optical networks. In addressing this opportunity, we propose to use a practical all-optical XOR network coding to leverage the conventional 1 + 1 optical path protection in transparent WDM optical networks. The network coding-assisted protection solution combines protection flows of two demands sharing the same destination node in supportive conditions, paving the way for reducing the backup capacity. A novel mathematical model taking into account the operation of new protection scheme for optimal network designs is formulated as the integer linear programming. Numerical results based on extensive simulations on realistic topologies, COST239 and NSFNET networks, are presented to highlight the benefits of our proposal compared to the conventional approach in terms of wavelength resources efficiency and network throughput.

1. Introduction

The explosively increasing demands of various bandwidth-intensive applications such as cloud and grid computing, high-definition video services and inter data center communications are posing serious challenges on optical transport networks for a greater network efficiency [1]. From architectural perspectives, transparent/all-optical optical networks have been an excellent candidate to sustain the explosive traffic growth with greater cost and operational efficiency as this architecture allows a signal remain in the optical domain for the entire route from the source to the destination and thus, eliminating costly and energy-consuming intermediate electronic processing [2]. Besides, that this technology operates on a wavelength granularity and being transparent to the bit-rate and protocols brings about a scalable route for network growths and upgrades [3].

Given an enormous amount of traffic, on the order of several Tb/s, being carried over a single fiber based on wavelength division multiplexing (WDM) technologies, the risk of traffic loss due to network failures would have massive impacts. As a recent example, Amazon has suffered five-hour outage due to the network failure and caused a tremendous loss of 150 millions dollars [4]. Indeed, in the era that the digital society has been clearly shaped and the business are essentially reliant on the continuity and robustness of information flows, securing the network against failures has become an integral part of network planning process [5–7]. Moreover, the protection requirements of today's communication networks is heightened by a necessity of rapid recovery time and latency as real-time services are on the manifold rise [1]. Among optical protection schemes against singe link failures, dedicated optical protection (1 + 1) stands out thanks to the immediate recovery speed and remarkable ease of operations and hence, has been widely implemented in backbone networks [8–10]. Dimensioning transparent WDM optical networks with 1 + 1 optical path protection such that the network performances are maximized and consequently, full benefits of this technology could be attained is critical to the success of next-generation optical transport networks. However, the highly desired features of near-instantaneous recovery and all-optical operations gives rises to challenges on network designs in which a number of particular constraints have to be taken into account compared to the classical opaque cases [11]. From the capacity efficiency perspective, the advantage of near-immediate protection is paid by a large amount of redundant network resources for maintaining duplicate signals on disjoint routes and hence, degrading the capacity efficiency [5].

Originally appeared in [12], network coding (NC) has been widely studied and developed to boost network throughput, reduce delay and

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https://doi.org/10.1016/j.yofte.2017.11.009
Received 5 June 2017; Received in revised form 7 October 2017; Accepted 11 November 2017

improve robustness in various networking research problems. In recent years, the application of NC has been extended to the scope of failure recovery in optical networks to enhance protection efficiency, collectively known as network coding-based protections [13–18]. The nature of protection requirements asking for disjoint routes appears as a good match to network coding to form coded signals rather than duplicating signals end-to-end, laying the foundation for reducing the backup capacity. This synergy has opened up new opportunities to combine the strength of near-instantaneous recovery achieved by dedicated protections and capacity efficiency potentially accomplished by network coding. Indeed, this combination has marked the departure from the traditional optical protection research, challenging the well-established compromise of trading capacity efficiency for speed recovery and vice versa. In literature, there are several works addressing the benefits of network coding for protection of optical networks. Those works are driven by the goal of looking for optimal network coding schemes from algebraic perspectives and theoretical viewpoints [15] or alternatively, determining the optimal designs to fully benefit from a given type of network coding [13]. However, the majority of existing works has been focused on opaque (O-E-O) networks in which multiple network coding operations could be performed on electrical domain with the electronic buffering and processing at each opaque network node. The potential of all-optical network coding schemes to the protection of transparent optical networks has not been adequately addressed in literature and therefore, motivated by this gap, we propose to take advantages of a practical all-optical XOR network coding scheme for leveraging the traditional 1 + 1 protection in transparent WDM optical networks. In favorable conditions, the protection flows of maximum two demands sharing the same receiving node could be encoded all-optically for a more efficient network resources usage while the working signals remain intact. The network coding-assisted protection solution is on a par with the traditional 1 + 1 protection in terms of speed recovery whereas the capacity efficiency could be potentially improved. In order to maximize the benefits empowered by NC, an important problem on routing and wavelength assignments of traffic demands, selecting pair of demands for encoding and determining coding node, coding links and coding wavelengths have to be optimally solved. We formulate such optimal designs of transparent WDM optical networks with 1 + 1 protection leveraged by the all-optical XOR operations in two typical scenarios. The first one, uncapacitated case, is characterized by the condition that the network capacity is large enough to accommodate all the traffic requests and thus, the objective is to minimize the wavelength resources. The second scenario, referred as the capacitated one, is targeted to maximize the network throughput in the condition of constrained bandwidth capacity. The effectiveness of the new protection proposal is highlighted in comparison with the traditional 1 + 1 protection over thorough simulations on realistic topologies, COST239 and NSFNET networks, and different traffic settings.

The rest of the paper is organized as follows. In Section 2, we review the related works on the application of network coding for protection in optical networks. In Section 3, we describe the framework for exploiting all-optical XOR operations to enhance the traditional 1 + 1 protection in detail. Mathematical models for optimal designs of transparent WDM networks with 1 + 1 protection improved by photonic XOR operations in both uncapacitated and capacitated scenarios are presented in Section 4. The performance evaluation of the new protection proposal in comparison with the conventional approach is presented in Section 5. Finally, Section 6 summarizes the paper.

2. Related works

Network coding has been proposed, investigated and developed to improve the protection performances in survivable optical networks and widely referred as the network coding-based protections [17,14,16,19].

The works from [20–22] pioneered in applying NC to optical unicast protection and showed that static network coding had the benefits of 1 + 1 protection but still allows a single unit of backup bandwidth to be multiplexed over N connections. This approach were named therefore as 1 + N protection and had been exploited to protect against single and multiple link failures using the structure of p-cycles. In [23], network coding was used to protect against node failures by transforming the problem to the multiple link failures case as consequences of the node failure. The initiatives from [24] extended network coding protection to multi-domain networks with a combination of 1 + 1 protection and dual homing and it was demonstrated that this technique could enable the network to survive under any node or link failure in each sub-domain. In [25], NC technique was demonstrated to reduce resource utilization in bandwidth-intensive 1 + 1 protection with the help of a network model with two sources and a common destination node. This work nevertheless considered only the conventional shortest path and load-balanced routing algorithms and thus, had a shortage of non-optimal solutions. In addressing this problem, the authors from [26] proposed mathematical formulations in the form of integer quadratic programming to achieve optimum routes for maximizing resource saving with the NC effect considering various two sources and a common receiver scenarios. Instead of limiting to considering two demands with shared destination at once, the work in [27] addressed the optimization problem in arbitrarily multiple demands. In the same context of 1 + 1 protection with NC, the research efforts from [28] extended the network coding scenarios to take into account the case of multiple sources and common destination and proposed an efficient heuristic for finding the near-optimal coding-aware routing. Traffic splitting in combination with network coding was addressed in [29,30] for improving the robustness efficiency. More recently, the network coding technique were also investigated in the context of elastic optical networks for improving the network efficiency with pioneering works from [31,32]. Network coding in all-optical networks was, for the first time, examined from both algorithmic and infrastructure perspectives in [33]. However, this research lacked to address the critical issue on wavelength assignments once the all-optical NC were adopted.

Our work is centered on the application of a practical coding scheme based on the all-optical XOR operation for leveraging the 1 + 1 dedicated optical path protection against single link failures in transparent WDM optical networks. All-optical XOR coding scheme has been backed by increasing experimental works [34–36] while other fancy coding schemes are still far from physical realization. In this scope, this work goes beyond the existing in literature by providing a framework for NC-assisted 1 + 1 protection and novel mathematical models for optimal network designs in order to maximize the benefits empowered by the all-optical XOR operations.

3. Leveraging 1 + 1 protection with all-optical XOR network coding

3.1. 1 + 1 dedicated protection node architecture

1 + 1 dedicated optical path protection is widely implemented in practice to provide immediate recovery to optical networks in case of failures with remarkable simplicity. Fig. 1 shows the node architecture of a generalized dedicated protection scheme in which two copies of the client data are transmitted simultaneously over the optical layer on dedicated resources (i.e., transponders and wavelengths) and on disjoint routes. At the destination node, the receiver receives two copies of the signal and is simply equipped with a decision circuitry for selecting the better one. It is important to note that with this generalized framework, the working and protection path do not have to be assigned the same wavelength (i.e., $\lambda_w \neq \lambda_p$) since there are dedicated transponders for modulating working and protection signals [37].