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Agile protection based on network coding against key link failures

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ABSTRACT

In order to provide cost-efficient and rapid protection against the key link failures dynamically, an intelligent p-cycle protection strategy based on network coding is proposed. Data units are combined from different links using network coding method at the on-cycle nodes, and then they are transmitted downstream for recovering data units lost due to failures. Under static traffic, an integer linear program (ILP) is formulated to provision the optimal p-cycles. Furthermore, according to the dynamic variation of the link importance degree, a heuristic cycle construction algorithm for generating, extending and contracting p-cycle is introduced to achieve intelligent and self-adaptive protection. The key of the proposed protection strategy is how to set the key link as a straddling link of the p-cycle as possible. The experiments demonstrate that the proposed strategy can guarantee instantaneous recovery of data units upon the failure of a key link with a low blocking rate and resource cost.

1. Introduction

Optical networks employing dense wavelength division multiplexing (DWDM) and wavelength routing are the most promising solution for future high-speed transport networks, especially because wavelength switched optical networks (WSONs) are proposed to provide and tear down light-paths quickly and effectively. Nevertheless, in realistic applications due to the irregularity of network topologies, the probability of each link to be occupied is different. Some links are always more likely to be used, which can be denoted as more important or key. Moreover, the randomness and burstiness of traffic distribution also make some links carry more data units in WSONs. Obviously, the disruption of the links with higher occupied probability or more carried traffic would bring larger amount of data loss. As a consequence, the network throughput would be harshly degraded and the robustness of system would be shattered [1–3]. Therefore, to ensure the network performance, it is essential to provide efficient protection for these relatively important key links in WSONs.

Obviously, key links are mainly determined by both the network topology and traffic distribution. It is noteworthy that the key links are generated dynamically because of the uncertain variation of the traffic flow. If a dedicated path protection is provided against the key link failures, the mass of network resources will be consumed. This may bring high blocking rate and low resource utilization. On the other hand, the shared path protection can reduce overhead efficiently, but due to failure detection and data rerouting, it will increase the recovery delay of loss data dramatically [4,5]. In order to reduce the protection cost and still provide instantaneous recovery in the meanwhile, the technique of network coding [6] has recently been applied to the problem of network protection. As described in [7,8], after data units from multiple disjoint links are fused at the intermediate nodes, the coded data and the traffic data are simultaneously transmitted on a shared protection path and the working paths similar to the dedicated protection. In case a working link fails, the receiver node would implement decoding from the two received data copies to recover the original data. So the recovery speed of dedicated protection can be achieved with the cost of shared protection. To take advantage of the p-cycle that combines ring-like fast restoration with mesh-like capacity efficiency [9], Kamal initially introduced the network coding protection using p-cycle in [10]. Furthermore, this idea is described in more detail and depth in [11]. Data units are coded at sources and destinations, and transmitted in two opposite directions on p-cycles, such that when a link on the primary path fails, data can be recovered from the p-cycle using simple modulo 2 addition. The strategy allows fast and resource-efficient recovery from failures [12]. However, the protection cycles must be recalculated in the event of the change of network environment because it uses the traditional p-cycle configuration method. This will take a long time to not adapt the request of dynamic network. In [13], paths are used to carry the linear combinations instead of cycles. The protection path must pass through all end-nodes of the protected connections, and be link-disjoint from the paths used by the protected connections. Moreover, to ensure data synchronization, the data round

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numbers are recorded in the local buffers of each node. Only data units transmitted from the same round are combined. This method is more flexible and simple than network coding protection using p-cycles, but its defect is that finding so suitable protection paths is very difficult in reality. Above all, the existing network coding protection technologies mainly concentrate under static network traffic, without considering the dynamical characteristic that the key links generate in actual network.

Consequently, in this paper we propose a network coding-based intelligent p-cycle (NCIP) protection strategy to provision agile protection against the key links failures. With the combination of simple coding method and bidirectional p-cycle technology, a novel protection model is established. Through detailed analysis, it is demonstrated the fault recovery time of straddling links is much less than that of on-cycle links. And according to the evaluation under static and dynamic conditions, the key links in the network could be determined accurately. In order to make the key links become the straddling links of p-cycles as possible, an integer linear program model and a heuristic dynamic cycle construction algorithm are proposed. The intelligent protection for all key links would be realized adaptively with cost-efficient resource and rapid recovery speed.

The new protection strategy is related to the techniques of [11,13]. Our theoretical basis is still the same, which is based on network coding. However, the proposed strategy improves upon the previous techniques in several aspects. Firstly, instead of undifferentiated protection against the link failures, we put emphases on these key links playing an important role in the networks. With the variation of traffic data, the new strategy can provide agile and self-adaptive protection for the dynamic key links. Secondly, to meet the new requirement of dynamic key links aware consideration, the network model is established by combining the advantages of fast bidirectional p-cycle data transmission in [11] and simple data coding synchronization in [13]. Thirdly, against the key link failures under static network, we formulate the ILP off-line to provide cost effective protection based on network coding according to the established network model. Lastly, against the key link failures under dynamic network, a heuristic new cycle construction algorithm is designed to respond the constantly changing traffic rapidly. Overall, these improvements result in a simple and scalable protocol that can be implemented in an agile way.

The rest of the paper is organized as follows. In Section 2 we introduce the protection model and make a comparison between the recovery time of on-cycle links and straddling links. Section 3 illustrates the main idea and implementation procedure of the proposed strategy in detail, including the judgment of key links, the establishment of the ILP, and the construction of dynamic cycle. Section 4 shows the simulation results in order to evaluate some performance metrics, e.g. resource utilization rate, outage times and blocking probability. Finally, conclusions are outlined in Section 5.

2. Network model

Combining routing with coding, network coding is a novel information exchange technology. Its core concept is to process the information from different links at the intermediate node by linear or nonlinear coding operation, and then the combined information would be forwarded downstream. Obviously, the node plays a role of encoder or decoder equipment, and the information transmission efficiency can be increased significantly. As stated above, one important application of network coding is to jointly protect a number of link disjoint paths.

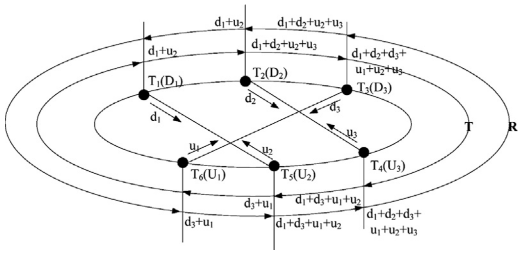

Fig. 1. p-Cycle protection model based on network coding.

In our network model, the data units are simultaneously transmitted along the p-cycle clockwise (T cycle) and counterclockwise (R cycle) similar to [11]. As shown in Fig. 1, there is a bidirectional p-cycle T_1–T_2–T_3–T_4–T_5–T_6–T_1 and three bidirectional straddling links T_1–T_5, T_2–T_4 and T_3–T_6. All on-cycle nodes would be divided into two ordered sets D and U, and be numbered one by one. Assume that each end node of the straddling link sends the data units simultaneously in different rounds. Different from [11], the nodes D_1 and U_1 perform encoding operation using simple modulo 2 addition for the received data units from the opposite end nodes of straddling link and their own data units which belong to the same round. Then the combined data units will be transmitted on the T cycle and the R cycle, respectively. The next node will add data units from the on-cycle and straddling links to its own data units which belong to the same round, and continue to forward the combined data units downstream [13]. Thus the network model integrates the merits of fast recovery speed of p-cycle and simple data synchronization at the same round, so that it is better for the dynamic network.

Suppose that the straddling link between nodes D_2 and U_3 fails, node U_3 will execute decoding for the data units from the T cycle and the R cycle to recover the data d_2. The fault recovery time could be expressed as follows

$$\tau_{U_3} = \max\{\tau_{U_2,D_1} + \delta^T_{D_1,U_3}, \tau_{D_3,U_1} + \delta^R_{U_1,U_3}\} - \tau_{D_2,U_3} \tag{1}$$

where τ_{U_2,D_1}, τ_{D_3,U_1} and τ_{D_2,U_3} are the propagation delay over the straddling (U_2,D_1), (D_3,U_1) and (D_2,U_3), respectively. $\delta^T_{D_1,U_3}$ is the propagation delay between nodes D_1 and U_3 on the T cycle. Similarly, $\delta^R_{U_1,U_3}$ is the delay between nodes U_1 and U_3 on the R cycle. Assume that any node transmits its data unit on each straddling link at the almost same time, that is, $\tau_{U_2,D_1} = \tau_{D_3,U_1} = \tau_{D_2,U_3}$, the fault recovery time is

$$\tau_{U_3} = \max\{\delta^T_{D_1,U_3}, \delta^R_{U_1,U_3}\} \tag{2}$$

When an on-cycle link fails, e.g., between nodes U_2 and U_3, the node U_2 would send the data $d_3{}'$ to node U_3 for recovering original data units after sensing the failure accurately. The fault recovery time could be represented by Eq. (3).

$$\tau'_{U_3} = \delta^R_{U_3,D_3} + F + \delta^R_{D_3,U_3} = F + \delta \tag{3}$$

$\delta^R_{U_3,D_3}$ and $\delta^R_{D_3,U_3}$ in the above equation are the propagation delay from node U_3–D_3 and from node D_3–U_3 along the R cycle, respectively. F is the fault detection and location time. δ is the propagation delay around the p-cycle.

To illustrate the difference between the fault recovery time of straddling links and on-cycle links, we assume that $T_j - T_k$ and $T'_j - T'_k$ are the straddling link and the on-cycle link of p-cycle P, respectively. The original sending nodes of T cycle and R cycle are N_t (let it be T_1) and N_r (let it be T_n), respectively. When the straddling link $T_j - T_k$ fails, the fault recovery time at on-cycle node T_k is given by

$$\tau_{T_k} = \max(\delta^R_{N_r,T_k}, \delta^T_{N_t,T_k}) \tag{4}$$