Computer Networks 58 (2014) 2–12

Contents lists available at ScienceDirect

Computer Networks

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

Localizing link failures in all-optical networks using monitoring tours

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ARTICLE INFO

Article history:
Received 5 March 2013
Accepted 29 July 2013
Available online 2 September 2013

Keywords:
Failure localization
Link failures
Monitoring cycles
Monitoring paths
Monitoring tours

ABSTRACT

In this paper, we introduce the concept of monitoring tours (m-tours) to uniquely localize all possible failures up to k links in all-optical networks. We establish paths and cycles that can traverse the same link at most twice (forward and backward) and call them m-tours. An m-tour is different from other existing schemes such as m-cycle and m-trail, which traverse a link at most once. Closed (open) m-tours start and terminate at the same (distinct) monitor location(s). Each tour is constructed such that any shared risk linked group (SRLG) failure results in the failure of a unique combination of closed and open m-tours. We prove that k-edge connectivity is a sufficient condition to localize all SRLG failures with up to k-link failures when only one monitoring station is employed. We introduce an integer linear program (ILP) and a greedy scheme to find the monitoring locations to uniquely localize any SRLG failures with up to k links. We provide a heuristic scheme to compute m-tours for a given network. We demonstrate the validity of the proposed monitoring method through simulations. We show that our approach using m-tours significantly reduces the number of required monitoring locations compared to previously developed techniques.

1. Introduction

The high data rates offered by optical transmission technology has increased the number of multimedia and interactive applications over the Internet in the past few years. However, the increased data rate does also increase the amount of data lost due to temporary service disruption caused by fiber cuts or component failures. Therefore, fault detection and localization becomes one of the most important issues in a network. Although single link failures are more common, multiple link failures occur due to shared risks. Such risks include the routing of fibers through the same duct, failure of a link while another link is under maintenance, or natural disasters that cause links traversing a region to fail.

Fault detection and localization may be performed at the physical layer by employing optical power detection and optical spectrum analysis [1,2]. To detect faults, monitors placed at several network locations generate an alarm whenever a fault occurs. By observing the generated alarms, the precise location of the fault may be identified. Several researchers have developed methods for localizing failures by observing monitor alarms generated by monitors [3–7]. Conventional link based monitoring schemes need one monitor at each communication link. In [8], an adaptive technique for fault diagnosis using "probes" was presented. According to this scheme, probes are established sequentially, each time using information about already established probes. While sequential probing helps achieve adaptiveness, it also increases the fault localization time. In [9], a non-adaptive fault diagnosis approach was developed based on establishing a set of probes. The techniques presented in [8,9] assume that any node can generate and terminate (analyze) a probe. Thus, any node could be a monitor. As monitoring of signals in the optical domain is

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http://dx.doi.org/10.1016/j.comnet.2013.07.018

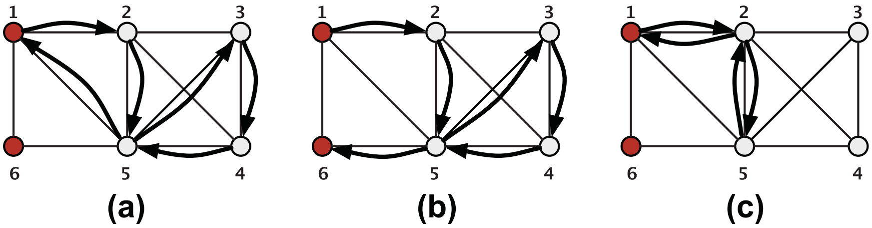

Fig. 1. Types of monitoring probes. Nodes 1 and 6 are monitoring stations. (a) Monitoring cycle (1–2–5–3–4–5–1); (b) monitoring path (1–2–5–3–4–5–6); (c) monitoring tour (1–2–5–2–1).

expensive, it is imperative that the number of nodes employing monitors is minimized. In order to minimize the number of monitors used for fault detection, [1,3] provided an algorithm for finding optimal monitor placement.

To detect and localize failures in a more efficient manner, m-cycles [4,5] and m-trails [6,7,10,11] were proposed. In the m-cycle scheme, a cycle that starts and ends at the same node is employed to monitor the network condition. The m-trail removes the cycle constraint and it is possible to start and terminate at different monitor nodes. For the m-trails and m-cycles, it is assumed that one monitor per cycle/trail is required and a cycle/trail can pass through a node several times but a link at most once. Since the minimum number of trails/cycles required is $\lceil \log (F+1) \rceil$, where F is the number of failures to localize, we need at least $\lceil \log (F+1) \rceil$ monitors. It is worth noting that several of the monitors could be placed at the same node. As the monitors are expensive, it is practical to assume that a node may employ only one monitor and that monitor could be timeshared across different trails/paths.

In [12,13], the authors used monitoring paths and cycles[1] to localize single link and Shared Risk Link Group (SRLG) failures. They proved that $(k+2)$-edge connectivity is necessary and sufficient to uniquely localize all SRLG failures involving up to k links with one monitor. If the network is not $(k+2)$-edge-connected, then the minimum number of monitors and their placement are identified. In addition, the authors develop a generic method for computing monitoring cycles and paths by merging all the monitors in the network and computing monitoring cycles. When the monitoring nodes are expanded, monitoring cycles/paths are obtained to uniquely localize all failures. The problem of localizing SRLG failures using m-trails was also studied in [14,15].

One of the major drawbacks of the monitoring cycles/paths/trails based approaches is that they all assume a link may be traversed in only one direction by a cycle/path/trail. In practice, links are directional due to the use of in-line amplifiers. Thus, bi-directional links are realized in practice using two unidirectional links running in opposite directions. Thus, we may allow a probe to traverse a link in both directions (similar to that employed in [8,9]). We refer to such probes as *monitoring tours* (m-tours). Monitoring cycles/paths/trails are then simply a special case of monitoring tours. Since the number of monitors that need to be employed in the network is significantly reduced when employing tours, the average length of a tour may increase. We assume that sufficient optical regenerators are deployed along the fiber to amplify the degraded signals and the degradation in the signal quality is measurable after these regenerations.

Fig. 1 shows examples of a monitoring cycle, path, and tour. Nodes 1 and 6 are assumed to be the monitoring stations. The monitoring cycle starts and ends at the same monitoring station. The monitoring path starts and ends at distinct monitoring stations. The monitoring cycle and path shown here are "non-simple" cycle and path, respectively, as node 5 appears twice. By allowing a probe to traverse a link at most twice, once in each direction, the approach using m-tours can enrich the probe paths and increase the flexibility for the localization problem. Our goal in this paper is to study the properties of localizing link failures using monitoring tours and evaluate the trade-offs when compared to employing only monitoring cycles and paths.

1.1. Contributions

In this paper, we show that to uniquely localize SRLG failures involving up to k link failures with one monitor and m-tours, it is necessary and sufficient that the link graph of the given network is k-vertex-connected and the degree of the monitor node is at least k. On the other hand, in [13], the authors showed that $(k+2)$-edge connectivity is a necessary and sufficient condition to localize up to k link failures with a single monitor and cycles. Therefore, by using tours, we can mitigate the connectivity condition and greatly reduce the number of monitors required to localize up to k links failures. According to [14,15], the monitoring cost is more important than the bandwidth cost (length of a monitoring cycle/path/tour) in the total cost. By reducing the number of monitors required, we can significantly save the monitoring cost and simplify network management, which is our objective in this study.

Next, we identify the necessary and sufficient conditions on the placement of monitors if the given network does not satisfy the connectivity requirement to localize with one monitor. We develop an integer linear program and a greedy heuristic to compute the minimum number of monitors required. We show that in certain situations, the computation

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[1] The monitoring paths and cycles are the same as m-trails and m-cycles. The monitoring paths start and end at distinct monitoring nodes, while monitoring cycles start and end at the same monitoring node. Both cycles and paths may be non-simple, where a node may be traversed multiple times.