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Dual-Link Failure Resiliency through FIPP and FDPP

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Abstract: Networks employ link protection to achieve fast recovery from link failures. While the first link failure can be protected using link protection, there are several alternatives for protecting against the second failure. This paper formally classifies the approaches to dual-link failure resiliency. One of the strategies to recover from dual-link failures is to employ link protection for the two failed links independently, which requires that two links may not use each other in their backup paths if they may fail simultaneously. Such a requirement is referred to as backup link mutual exclusion (BLME) constraint and the problem of identifying a backup path for every link that satisfies the above requirement is referred to as the BLME problem. This paper develops the necessary theory to establish the sufficient conditions for existence of a solution to the BLME problem. Solution methodologies for the BLME problem is developed using two approaches by: 1) formulating the backup path selection as an integer linear program; 2) developing a polynomial time heuristic based on minimum cost path routing. The ILP formulation and heuristic are applied to six networks and their performance is compared with approaches that assume precise knowledge of dual- link failure. It is observed that a solution exists for all of the six networks considered. The heuristic approach is shown to obtain feasible solutions that are resilient to most dual-link failures, although the backup path lengths may be significantly higher than optimal. In addition, the paper illustrates the significance of the knowledge of failure location by illustrating that network with higher connectivity may require lesser capacity than one with a lower connectivity to recover from dual-link failures.

Keywords: FIPP, FDPP, WDM, SRLG, BLME, ARPANET, NSFNET, NJ-LATA, ILP.

I. INTRODUCTION

The ever-increasing transmission speed in the communication networks calls for efficient fault-tolerant network design. Today's backbone networks employ optical communication technology involving wavelength division multiplexing (WDM). A link between two nodes comprises of multiple fibers carrying several tens of wavelengths with transmission speed on a wavelength at 40 Gb/s. Due to the large volume of information transported, it is necessary to reduce the resource unavailability time due to failures. Hence, efficient and fast recovery techniques from node and link failures are mandated in the design of high-speed networks. As link failures are the most common case of the failures seen in the networks, this paper restricts its scope to link failures alone. Optical networks of today operate in a circuit-switched manner as optical header processing and buffering technologies are still in the early stages of research for wide-scale commercial deployment. Protecting the circuits or connections established in such networks against single-link failures may be achieved in two ways: path protection or link protection. Path protection attempts to restore a connection on an end-to-end basis by providing a backup path in case the primary (or working) path fails. The backup path assignment may be either independent or dependent on the link failure in the network. For example, a backup path that is link-disjoint with the primary path allows recovery from single-link failures without the precise knowledge of failure location. On the other hand, more than one backup path may be assigned for a primary path and the connection is reconfigured on the backup path corresponding to the failure scenario that resulted in the primary path failure. The former is referred to as failure-independent path protection (FIPP) while the latter is referred to as failure-dependent path protection (FDPP). Link protection recovers from a single link failure by rerouting connections around the failed link. Such a recovery may be achieved transparent to the source and destination of the connections passing through the failed link. Link protection at the granularity of a fiber switches all of the connections on a fiber to a separate (spare) fiber on the backup path. The time needed to detect the fault, communicate to the end-nodes, re-initiate connection requests on the backup paths, and reconfigure the switches at the intermediate nodes could sometimes cause the layers above the optical layer to resort to their own restoration solutions. Link protection reduces the communication requirement as compared to path protection, thus providing fast recovery. However, the downside of link protection is that its capacity requirement is higher than that of path protection, specifically when protection is employed at the connection granularity Algorithms for protection against link failures have traditionally considered single-link failures (for a detailed description on protection approaches, refer to). However, dual link failures are becoming increasingly important due to two reasons. First, links in the networks share resources such as conduits or ducts and the failure of such shared resources result in the failure of multiple links. Second, the average repair time for a failed link is in the

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order of a few hours to few days , and this repair time is sufficiently long for a second failure to occur. Although algorithms developed for single-link failure resiliency is shown to cover a good percentage of dual-link failures , these cases often include links that are far away from each other. Considering the fact that these algorithms are not developed for dual-link failures, they may serve as an alternative to recover from independent dual-link failures. However, reliance on such approaches may not be preferable when the links close to one another in the network share resources, leading to correlated link failures.Dual-link failures may be modeled as shared risk link group (SRLG) failures. A connection established in the network may be given a backup path under every possible SRLG failure. This approach assumes a precise knowledge of failure locations to reconfigure the failed connections on their backup paths. An alternative is to protect the connections using link protection, where only the nodes adjacent to the failed link (and those involved in the backup path of the link) will perform the recovery. The focus of this paper is to protect end-to-end connections from dual-link failures using link protection.

II. THEORY

Consider a network represented as a graph G(N, L), where N and L denote a set of nodes and undirected links, respectively. The nodes are numbered from 1 through |N|. A link l ∈ L is assumed to be bi-directional. Let x1 and yl denote the identifiers of the nodes connected by link l such that x Let A represent the set of directional links, or arcs, in the network. An arc from node i to j is denoted as (i, j).The failure of link l is assumed to affect the arcs in both directions. Let F denote the set of dual link failures to be tolerated. An element f ∈ F consists of exactly two undirected links, or correspondingly four directed arcs.

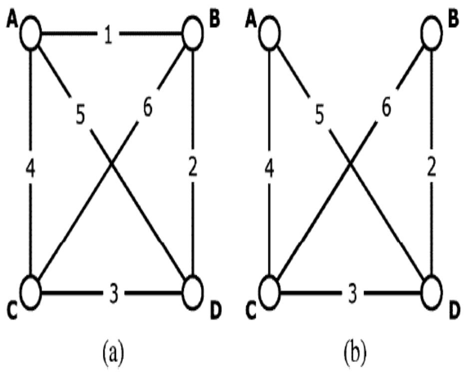

Fig. 5. (a) Example network. (b) Network after failure of link 1.

III.SUFFICIENT CONDITION FOR EXISTENCE OF A SOLUTION

Three-edge-connectivity is a necessary condition for a network to be resilient to dual link failures. It is also sufficient that a network is three-edge-connected in order to obtain a solution for BLME problem, proved as follows. Assume that the given network is divided into |L| auxiliary graphs. An auxiliary graph Xl is constructed by removing link l from the original network: Xl= G(N, L − {l}). In each auxiliary graph Xl, the goal is to identify a path Pl from node xl to yl. Let θll be a binary variable that indicates whether link l is present in the backup path of link l: 1 if true, 0 otherwise.Let Γl be the boolean function that denotes the connectivity between nodes xl and yl in the auxiliary graph Xl, represented as a function of the variable set {θll: l ∈ Xl}.Consider the example network shown in Figure 5(a). The auxiliary graph corresponding to link 1 is shown in Figure 5(b). The boolean function representing the connectivity between nodes A and B is shown in Equations (1) and (2) in Sum-of-Product and Product-of-Sum forms, respectively It may be observed that Γl is an unate function, hence has a trivial solution. If the function Γl evaluates to 1 (true) for some input combination of {θll: l ∈ Xl}, then there exists a path between the nodes xl and yl in Xl .Observation-1: The connectivity functions Γl and Γl are independent of each other for any two distinct links l, l ∈ L, i.e. the functions Γl and Γl do not have any variables in common.Observation-2: If Γl= 0 for some l ∈ L, then the network is one-edge connected. The failure of link l disconnects the network. Conversely, if a network is at least two-edge-connected, then Γl = 0, ∀l ∈ L.The different connectivity functions are related to each other through the BLME constraint. The BLME constraint corresponding to a dual link failure f ∈ F is written in the sum of-product and product-of-sum forms as shown Equations (3) and (4), respectively The BLME problem is then written as a boolean satisfia-bility problem, denoted by Θ, as shown in Equation (5). It is observed that Θ is a function of the set of variables {θll: l ∈ Xl, l ∈ L}. If the boolean function Θ is identically 0for all input combinations, then the BLME problem does not have a feasible

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solution. If Θ evaluates to a non-zero function, then there exists an input combination for which the function evaluates to 1 (true). Theorem 1: If a network is at least two-edge-connected and Θ = 0, then there exists a dual link failure f ∈ F that disconnects the graph. Proof: Given that the network is at least two-edge-connected, Γl= 0, ∀l ∈ L. Clearly, Δf= 0, ∀f ∈ F.Therefore, 1) ∧l∈LΓl= 0 and 2) ∧f∈FΔf= 0.Hence, for Θ = 0, the conjunction of a combination of connectivity terms (Γl) with one of the BLME constraints results in an identically zero function. A dual link failure scenario f involving links l and l has the BLME constraint as shown in Equation (3).

$$\Gamma_1 = (\theta_{12} \wedge \theta_{15}) \vee (\theta_{14} \wedge \theta_{16}) \vee (\theta_{12} \wedge \theta_{13} \wedge \theta_{14}) \vee (\theta_{13} \wedge \theta_{15} \wedge \theta_{16}) \tag{1}$$

$$= (\theta_{14} \vee \theta_{15}) \wedge (\theta_{12} \vee \theta_{16}) \wedge (\theta_{12} \vee \theta_{13} \vee \theta_{14}) \wedge (\theta_{13} \vee \theta_{15} \vee \theta_{16}) \tag{2}$$

$$\Delta_f = \neg(\theta_{\ell\ell'} \wedge \theta_{\ell'\ell}) \tag{3}$$

$$= (\neg\theta_{\ell\ell'} \vee \neg\theta_{\ell'\ell}) \quad \text{where} \quad \ell, \ell' \in f; \forall f \in \mathcal{F} \tag{4}$$

$$\Theta = \left(\bigwedge_{\ell \in \mathcal{L}} \Gamma_\ell\right) \wedge \left(\bigwedge_{f \in \mathcal{F}} \Delta_f\right) \tag{5}$$

$$\bigwedge_{\ell^* \in \mathcal{L}} \Gamma_{\ell^*} = (\theta_{\ell\ell'} \wedge \theta_{\ell'\ell}) \wedge \left(\Gamma_\ell|_{\theta_{\ell\ell'}=1}\right) \wedge \left(\Gamma_{\ell'}|_{\theta_{\ell'\ell}=1}\right) \wedge \left(\bigwedge_{\ell'' \in \mathcal{L}, \ell'' \neq \ell, \ell'} \Gamma_{\ell''}\right) \quad \ell, \ell' \in f \text{ for some } f \in \mathcal{F} \tag{6}$$

$$= \left[\theta_{\ell\ell'} \wedge \left(\Gamma_{\ell\ \theta_{\ell\ell'}=1}\right)\right] \wedge \left[\theta_{\ell'\ell} \wedge \left(\Gamma_{\ell'}|_{\theta_{\ell'\ell}=1}\right)\right] \wedge \left(\bigwedge_{\ell'' \in \mathcal{L}, \ell'' \neq \ell, \ell'} \Gamma_{\ell''}\right) \tag{7}$$

Objective function.	Minimize $\sum_{\ell \in \mathcal{L}} \sum_{\ell' \in \mathcal{L}} \alpha_{\ell\ell'}$	
Graph constraint (GC).	$\alpha_{\ell\ell} = 1$	$\forall \ell \in \mathcal{L}$
BLME constraint (BLMEC).	$\alpha_{\ell\ell'} + \alpha_{\ell'\ell} + F_{\ell\ell'} \leq 2$	$\forall \ell, \ell' \in \mathcal{L}$ and $\ell \neq \ell'$
Ring constraint (RC).	$2\beta_{\ell i} - \sum_{\ell' \in \mathcal{L}} \alpha_{\ell\ell'} C_{\ell' i} = 0$	$\forall \ell \in \mathcal{L}$ and $i \in \mathcal{N}$
Bounds.	$\alpha_{\ell\ell'} = \{0,1\}$	$\forall \ell, \ell' \in \mathcal{L}$
	$\beta_{\ell i} = \{0,1\}$	$\forall \ell \in \mathcal{L}$ and $i \in \mathcal{N}$

Fig. 6. ILP formulation of backup path selection with BLME constraint.

If the BLME constraint corresponding to dual link failure f combines with the conjunction of the connectivity functions resulting in an identically zero-function, then the conjunction of the connectivity terms must take the form as shown in Equation (6). Note that the first term of Equation (6) cancels the BLME constraint involving the links l and l resulting in a zero function for Θ. For any two distinct links l and l, Γl and Γl are independent of each other. Hence, Equation (6) implies that Γl and Γl must be of the form:Γl= θll∧ Γl|θll=1 Γl= θl l∧ Γl|θl l=1 The above equations imply that upon failure of link l, any path from nodes xl and yl must traverse link l and on failure of link l , any path from xl to yl must traverse link l. Links l and l are mutually dependent on each other for their backup paths. Therefore, the dual link failure f involving links l and l disconnects the network. Corollary: Given a three-edge-connected network, there exists a solution to the BLME problem under any arbitrary two link failures. Proof: The corollary follows from Theorem 1 by considering all dual link combinations in F. Assume that the BLME problem does not have a solution for a three-edge-connected network. Hence, Θ = 0. By Theorem 1, there exists a dual link failure f ∈ F that disconnects the network. However, no two link failures can disconnect the network as the network is three-edge-connected, resulting in a contradiction. Hence, Θ =0. Clearly, Θ = 1 (identically 1 for all input combinations) Hence, for a three-edge-connected network Θ evaluates to a non-trivial (non-zero, non-unity) boolean function, thus must evaluate to 1 for some input combination.

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IV. INTEGER LINEAR PROGRAM FORMULATION

The BLME problem is formulated as an Integer Linear Program (ILP) using undirected links. The central idea behind this ILP formulation is to view the network as |L| distinct graphs. Each graph, denoted as Gl, will provide a backup path for link l. Equivalently, each graph Gl will have a ring traversing through link l. Let Fll denote the existence of a failure f ∈ F such that l ∈ ψ and l ∈ ψ; 1 if true, 0 otherwise Let αll be a binary variable that indicates whether link l is present in graph Gl: 1 if present, 0 otherwise. Similarly, let βli be a binary variable that indicates whether node i is present in graph Gl or not: set to 1 if present, 0 otherwise. Let Cli denote whether node i is attached to link l or not: 1 if true, 0 otherwise. The formulation of backup path selection for all links satisfying BLME constraint is shown in Figure 6. The objective function is set to minimize the sum of the backup path lengths of all links, or equivalently the average backup path length of a link under a single link failure. The average backup path length under single link failure, denoted by H, is computed as:

$$\overline{H} = \left(\frac{1}{|\mathcal{L}|} \sum_{\ell,\ell' \in \mathcal{L}} \alpha_{\ell\ell'} \right) - 1. \qquad (8)$$

The constraints GC ensures that a graph Gl must contain a ring with link l present in the ring by forcing the corresponding link variables to take a value of 1. The BLME constraint ensures that for two links l and l that belong to L, if link l is present in Gl, then l is not present in graph Gl if the two links l and l may be unavailable at the same time. Otherwise, such a restriction is not imposed. The constraint RC ensures every graph has a ring, every node i that is present in a graph must have exactly two outgoing (or incoming) links. The above constraint introduces |L|×|N| additional variables βli to the formulation, however, they are strongly correlated to the link variables αll. The variables employed in the formulation are limited to take binary values using Bounds.

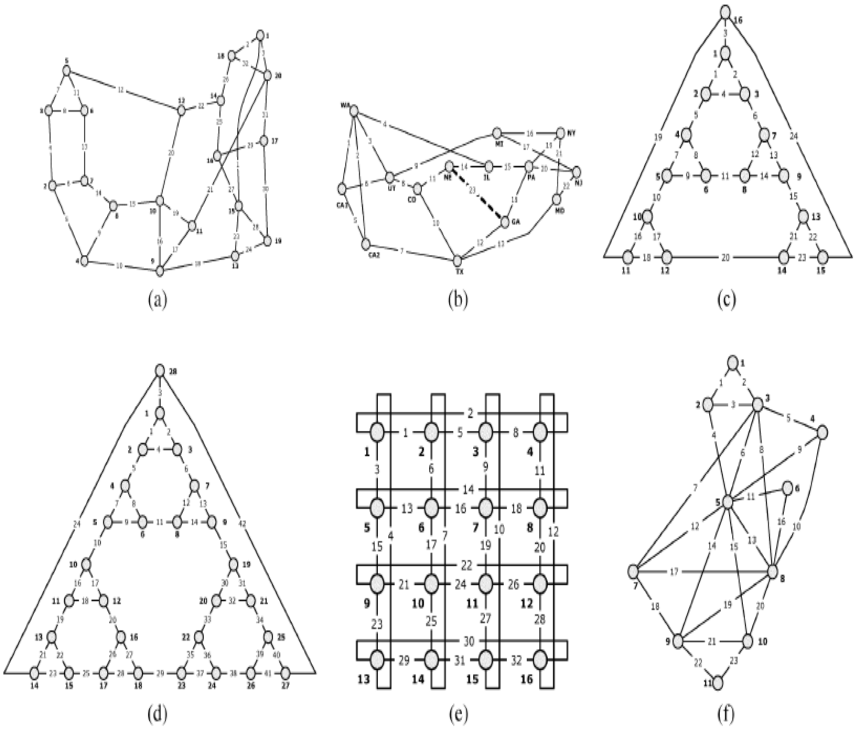

Fig. 10. Networks considered for performance evaluation. (a) ARPANET (20 nodes, 32 links). (b) NSFNET (14 nodes, 23 links). (c) Node-16 (16 nodes, 24 links). (d) Node-28 (28 nodes, 42 links). (e) Mesh-4 × 4 (16 nodes, 32 links). (f) NJ-LATA (11 nodes, 23 links).

V. PERFORMANCE EVALUATION

The performance of the ILP and heuristic algorithm developed in this paper are evaluated by applying them to six networks as shown in Figure 10: (a) ARPANET; (b) NSFNET;(c) Node-16; (d) Node-28; (e) Mesh-4×4; and (f) NJ-LATA. All networks except NJ-LATA are three-connected. The NJ-LATA network is not three-connected as nodes 1,

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6, and 11 have degree 2 and is considered “as is” for performance evaluation. The formulation for the NJ-LATA network has been modified as outlined in Section III-B. The Node-16 and Node-28 networks are hypothetical networks used to test the limits of the ILP. All the nodes in these two networks have exactly three links connected to them, thus these two networks are minimally 3-connected. Dual-link failure scenarios occur in networks due to two reasons, as mentioned in Section I. First, link resources such as conduitor duct are shared by multiple links for ease of layout. Such sharing of resources is typically limited to links that are close to each other, such as adjacent links. Hence, dual-link failure scenarios under such shared resource failure typically affect only nearby links. The second case of dual-link failure scenario is due to the time required to repair a failed link. Before a failed link is repaired, another link in the network could fail; however, such failures are typically rare. If it can be assumed that most of the dual-link failures may be caused because of failures of shared resources, then it is of interest to identify backup path assignments by considering only failures of nearby links. Three kinds of dual-link failures are considered: 1) any arbitrary two link failures; 2) links that are one node away; and 3) links that are two nodes away. Note that any dual-link failure that will disconnect the network is not considered in computing the number of failures that can be tolerated.

VI. PERFORMANCE METRICS

The performance metrics considered specifically for the ILP solutions are: 1) solution time and 2) optimality bound. The optimality bound is relevant in scenarios where the ILP could not obtain optimal solution, but has a feasible solution with a known bound on optimality. The ILP is solved using the CPLEX 8.1 solver [15] on a single-processor Pentium4 2.53 GHz computer with 512 MB of RDRAM. The optimality bounds reported in this paper are those provided by the CPLEX solver. The metric that is considered specifically for heuristic is the number of dual-link failures that can be tolerated, as the heuristic is not guaranteed to recover from all dual-link failures.

VII. ILP RESULTS

Table I shows the results for the six networks to be resilient to any arbitrary two-link failure obtained using ILP with the objective to optimize the average backup path length under single-link failure scenario. The CPLEX program terminated due to insufficient memory for Node-28 and Mesh-4 4 networks. While this is indicative of the complexity of the problem, feasible solutions were obtained as intermediate values. The best value obtained before termination is reported for these networks. It is observed that the solution time increases with increase in the network size but decreases with an increase in average node degree. Note that NSFNET and NJ-LATA networks both have 23 links, however, the solution times are significantly different due to their connectivity. For scenarios where an optimal solution is not found, the value of optimality bound indicates the worst case deviation of best value from the optimal. It is to be noted that, although an optimal solution may not be obtained, a feasible solution is obtained failure disconnects the network were not present in more than one backup path, thus a reduction of four fibers was obtained. The high connectivity in the NJ-LATA network results in this reduction even when the objective function is not set to minimize capacity, which is purely coincidental. Such a reduction cannot be guaranteed for all networks. It is also observed that the average backup path length under dual-link failures (for Node-16 and Node-28 networks) may be lower than the average backup path length under single-link failure scenarios due to path pruning. for all the networks considered, confirming the existence of a solution. It is observed that a 200% additional capacity (two spare fibers) is required in all of the links of all of the networks except NJ-LATA. Such a requirement can be immediately deduced from the connectivity of the network. For example, whenever a link is necessary3 to keep the network three-connected, then such a link must have two spare fibers. Thus, the networks Node-16 and Node-28 will require 200% additional capacity even when only adjacent links may fail together. Such a 200% requirement in capacity may be reduced only on those links whose removal does not affect the three-connectivity property of the network. For example, the link between WA and UT in the NSFNET may be removed without affecting the three-connectivity property of the network. However, such a solution would have an increased average backup path length. For the NJ-LATA network, two of the three link pairs whose failure disconnects the network were not present in more than one backup path, thus a reduction of four fibers was obtained. The high connectivity in the NJ-LATA network results in this
reduction even when the objective function is not set to minimize capacity, which is purely coincidental. Such a reduction cannot be guaranteed for all networks. It is also observed that the average backup path length under dual-link failures (for Node-16 and Node-28 networks) may be lower than the average backup path length under single-link failure scenarios due to path pruning.

VIII. CONCLUSION

This paper formally classifies the approaches for providing dual-link failure resiliency. Recovery from a dual-link failure using an extension of link protection for single link failure results in a constraint, referred to as BLME

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constraint, whose satisfiability allows the network to recover from dual-link failures without the need for broadcasting the failure location to all nodes. The paper develops the necessary theory for deriving the sufficiency condition for a solution to exist, formulates the problem of finding backup paths for links satisfying the BLME constraint as an ILP, and further develops a polynomial time heuristic algorithm. The formulation and heuristic are applied to six different networks and the results are compared. The heuristic is shown to obtain a solution for most scenarios with a high failure recovery guarantee, although such a solution may have longer average hop lengths compared with the optimal values. The paper also establishes the potential benefits of knowing the precise failure location in a four-connected network that has lower installed capacity than a three-connected network for recovering from dual-link failures.

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