Innovative Method for Two Link Failure Protection
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Abstract—Internet is powered by the world wide optical network and hence, survivability of optical network is extremely important. Sometimes, the protection for the two failed links interfere with each other and as a consequence only one failure can be protected. In a large optical network, failure probability of two links with overlapping protection can be high, as these links will be very likely geographically closer. Also, two link failure protection makes the network more resilient by taking care of double failures having overlapping protection. An innovative method for network survivability against two link failure is introduced in this paper. Further, to take care of this scenario, double cycle method (DB) which uses two cycles to protect a link has been described in this paper. Integer linear program (ILP) is formulated for the proposed as well as DB method. It was observed that the proposed method is simpler and performs better than the DB method.

Index Terms—optical network, p-cycle, straddling link, two link failure.

I. INTRODUCTION

OPTICAL networks carry enormous amount of information. Failure of any element in an optical network even for a small duration can lead to large amount of information and revenue loss. Thus, it is important to build mechanism of survivability to take care of such failures. Survivability of a network is the ability of network to either maintain uninterrupted flow of information or minimize the outage period. In optical network, it is of great importance and therefore, it has been studied extensively by the researchers [1] [2].

Among various protection schemes, p-cycles are promising due to mesh like efficiency and ring like speed. P-cycle was first introduced by Grover [3] and since then it is a subject of great interest in the area of optical network survivability [4]. P-cycle can protect working capacity of on-cycle as well as straddling links. A straddling link is a chord of cycle with their nodes on cycle. When a straddling link fails p-cycle has two paths to reroute the traffic and hence, the capacity requirement in p-cycle is reduced to half of working capacity protected in the straddling links. A single copy of p-cycle can provide unit capacity protection to on-cycle links and, two unit capacity protection to straddling links on it.

II. PROPOSED PROTECTION METHOD

Normally a copy of p-cycle can protect unit capacity on on-cycle link and two units of capacity on a straddling link. A straddling link has two alternative paths on p-cycle for restoration, and this attribute of p-cycle is employed in the proposed method to protect optical network against two simultaneous link failure. In the proposed protection method, all the links having working capacities are protected only as straddling links and on-cycle protection is not used. In case, a p-cycle is shared among multiple straddling links, the number of copies of p-cycles are taken to be equal to the highest capacity straddling link. Number of copies of p-cycles to protect a straddling link is kept equal to the capacity of straddling link. If the capacity of the straddling link to be protected is an odd number, then the number of copies of p-cycle is kept unit capacity higher than the capacity of the straddling link. Even number of copies of p-cycle are required to ensure protection where the capacity of straddling links sharing the p-cycle are equal and odd number. For example, if capacity of each straddling links to be protected is three, then the copies of p-cycle should be four. Restoration takes place in two different ways depending on which two links have failed (two straddling links, or a straddling and an on-cycle link).

When two straddling links fail simultaneously, highest capacity straddling link uses half of the capacity of p-cycle, and the other failed link uses the remaining capacity of the p-cycle. When a straddling link and an on-cycle link fail then the straddling link uses the intact alternative path on p-cycle for restoration. Consider a p-cycle protecting three straddling links e1, e2 and e3 as shown in Fig. 1. Assume that e1 is the highest capacity straddling link with w1 capacity protected by the p-cycle. The number of copy of p-cycle required as per our algorithm to protect network against two link failure will be w1 for w1 even and w1 + 1 for w1 odd. In case of failure of two straddling links e1 and e2 in Fig. 1 (a), half of the w1 copies of p-cycle will be used to restore e1. Link e2 is restored from the remaining half copies of the p-cycle. In case of failure of a straddling link and an on-cycle link as shown in Fig. 1(b), w1 capacity of the intact alternative path on p-cycle will restore link e1. Link f is restored by some other p-cycle of the network as it must have also been given double fault protection. The method described here is simple than the method described in [5], as it does not require two p-cycles to protect a link. Computation time required is also significantly less. Spare capacity required is also more efficient. The efficiency is even better for optical network with higher average nodal degree.

A. ILP for proposed method

The objective of this ILP is to find the minimum spare capacity required to protect optical network against two link
failures using the proposed protection method. We find the minimum spare capacity needed for single fault protection when only straddling link protection is used. Thereafter, number of p-cycles needed are simply doubled to provide double fault tolerance.

**Notations**

- \( S \) = set of spans in the graph.
- \( P \) = set of cycles in the graph.

\( x_{i,p} \) is the amount of demand capacity of link \( i \) protected by unit capacity of p-cycle \( p \) for single fault tolerance and only straddling protection.

\[
x_{i,p} = \begin{cases} 2 & \text{if link } i \text{ is straddling link on p-cycle } p, \\ 0 & \text{otherwise}. \end{cases}
\]

\( \delta_{i,j} = \begin{cases} 1 & \text{if span } i \text{ is on cycle } j, \\ 0 & \text{otherwise}. \end{cases} \)

**Variables**

- \( s_i \) = spare capacity on span \( i \).
- \( w_i \) = working capacity on span \( i \).
- \( c_i \) = cost of unit capacity of span \( i \).
- \( n_p \) = number of copies of p-cycle \( p \).
- \( n_{i,p} \) = number of copies of p-cycle \( p \) required to protect working capacity of link \( i \) in single fault tolerance scenario.

**Minimize:**

\[
\sum_{i \in S} c_i s_i. \tag{1}
\]

**Subject to:**

\[
\sum_{p \in P} x_{i,p} n_{i,p} \geq w_i; \quad \forall i \in S. \tag{2}
\]

\[
n_p \geq 2n_{i,p}; \quad \forall i \in S; \forall p \in P. \tag{3}
\]

\[
s_i \geq \sum_{j \in P} n_j \delta_{i,j}; \quad \forall i \in S. \tag{4}
\]

\[
n_p \geq 0, n_{i,p} \geq 0; \quad \forall i \in S; \forall p \in P. \tag{5}
\]

In equation (1) the objective function that minimizes the spare capacity on each link is defined. Constraint (2) ensures that the protection capacity on p-cycle is sufficient to protect working capacity on link \( i \) under single fault tolerance scenario. Constraint (3) selects the maximum number of copies of p-cycles \( p \) required to provide protection to straddling links, on simultaneous failure of two links. Constraint (4) ensures that spare capacity on each link is sufficient to form the p-cycles.

**III. DB METHOD**

The most intuitive method for 100% dual link failure protection is to protect each link of the network with two p-cycles as described in [5]. The pair of p-cycles chosen to protect a link must have link disjoint backup paths as shown in Fig. 2. We have considered bidirectional graph G (N, L), and an alternative ILP is formulated to use the concept of using two p-cycles for protecting each link. Here N is the number of nodes and L is the number of links. Set of cycles, and set of pair of p-cycles for each link are precomputed and given as input to the optimization model.

For each link, pair of p-cycles are chosen independently. The p-cycles are shared for protecting more than one link. Thus a p-cycle can pair with different p-cycles simultaneously. In some cases same pair of p-cycles can protect two links. Simultaneous failure of two link having same pair of protecting p-cycles may lead to situation when, the failed links have only one p-cycle for protection. The spare capacity required in such case is higher. Possible scenarios when a pair of p-cycle can protect more than one link are shown in Fig. 3.
Fig. 3(a) shows the case in which two links \( i \) and \( j \) are on cycle on p-cycle \( p \) and straddling on p-cycle \( q \). If link \( i \) fails, protection is provided by one of the p-cycle from the pair. If second failure occur on the p-cycle which is used to restore the first failure, then traffic is diverted on the unused p-cycle of the pair. Link \( j \) is also protected by pair of p-cycle \( p \) and \( q \) in the same way. In case of simultaneous failure of link \( i \) and \( j \), p-cycle \( p \) fail to protect the links, and traffic for both the links is restored by \( q \). The required number of copies of p-cycles \( p \) and \( q \) should be sufficient to incorporate the two failure scenarios mentioned above. Number of copies of p-cycle \( p \) required will be the maximum of the working capacities of \( i \) and \( j \). Number of copies of \( q \) will be sum of half the capacities of \( i \) and \( j \) approximated to next higher integer (for non-integer sum).

To ensure protection for the three cases shown in Fig. 3(b), (c) and, (d), number of copies of p-cycle \( p \) and \( q \) required will be the one needed to protect the maximum of the capacities on link \( i \) and \( j \). In case of simultaneous failure of link \( i \) and \( j \), p-cycles \( p \) and \( q \) protects link \( i \) and \( j \) respectively.

### A. ILP for DB method

This linear program finds minimum spare capacity required to form p-cycles, ensuring protection of each link against two simultaneous link failure using DB method.

**Notations**

- \( S \)=set of spans.
- \( P \)=set of cycles.
- \( Q_i \)=set of pair of p-cycles which protects span \( i \) and are disjoint or have only one link \( i \) as common on-cycle link, indexed as \( (p,q)_i \).

For a link \( i \) having \( (p,q)_i \) in their set \( Q_i \) we define \( x_{i,p,q} \) as follows,

\[
x_{i,p,q} = \begin{cases} 
1 & \text{if link } i \text{ is on cycle on p-cycle } p \\
2 & \text{if link } i \text{ is straddling link on p-cycle } p \\
0 & \text{otherwise.}
\end{cases}
\]

\[
\delta_{i,j} = \begin{cases} 
1 & \text{if span } i \text{ is on-cycle on p-cycle } j \\
0 & \text{otherwise.}
\end{cases}
\]

**Variables**

- \( s_i \)=spare capacity on span \( i \).
- \( w_i \)=working capacity on span \( i \).
- \( c_i \)=cost of unit capacity of span \( i \).
- \( n_i \)= number of copies of p-cycle \( j \).
- \( n_{i,p,q} \)=number of copies of p-cycle \( p \) required to protect link \( i \) in pair with p-cycle \( q \) to protect link \( i \) against two simultaneous failure.
- \( n_{i,p} \)=number of copies of p-cycle \( p \) required to protect working capacity of link \( i \).

**Minimize:**

\[
\sum_{i \in S} c_i s_i 
\]  

\[
\text{(6)}
\]

**Subject to :**

\[
\sum_{(p,q) \in Q_i} [x_{i,p,q} n_{i,p,q} + x_{i,q,p} n_{i,q,p}] \geq 2 w_i; \quad \forall i \in S. \quad (7)
\]

If link \( i \) is on-cycle or straddling link on both \( p \) and \( q \),

\[
n_{i,p,q} = n_{i,q,p}; \quad \forall i \in S; \forall (p,q) \in Q_i. \quad (8)
\]

If link \( i \) is straddling link on \( q \) and on-cycle on \( p \),

\[
n_{i,p,q} = 2 n_{i,q,p}; \quad \forall i \in S; \forall (p,q) \in Q_i. \quad (9)
\]

\[
n_p = \sum_{q \in P, q \neq p} n_{i,p,q}; \quad \forall p \in P; \forall (p,q) \in Q_i. \quad (10)
\]

\[
n_p \geq n_{i,p} + n_{j,p,q}; \quad \forall i \in S; \forall (p,q) \in Q_j \cap Q_i; \quad (11)
\]

\[
s_i \geq \sum_{j \in P} n_j \delta_{i,j}; \quad \forall i \in S. \quad (12)
\]

\[
n_p \geq 0, n_{i,p} \geq 0, n_{i,p,q} \geq 0; \quad \forall i \in S; \forall p \in P; \forall (p,q) \in Q_i. \quad (13)
\]

The objective function (6) minimizes the spare capacity on each link. Constraint (7), (8) and (9) ensure full protection of working capacity of each link against two simultaneous link failure. Constraint (10) calculates the number of copies of a p-cycle \( p \) required to protect a link \( i \) as the sum of number of copies of the p-cycle \( p \) in pair with other p-cycles \( q \) required to protect the link \( i \). Constraint (11) ensures that the number of copies of p-cycle is sufficient to protect the link with highest working capacity. Constraint (12) also takes care of the case when two links share same pair of p-cycles, as described in this section earlier and illustrated by Fig. 3. Constraint (13) ensures that spare capacity on each link is sufficient to form the p-cycles.

### IV. RESULTS AND DISCUSSION

ILP formulation is carried out on scilab 5.5, and ILOG CPLEX 9 is used to solve the ILP on AMD Opteron (tm) 1.8 GHz CPU. The number of variables required in the proposed method is of the order of \( O(L \times P) \) where \( L \) is the number of links, and \( P \) is the number of cycles. In the proposed method number of variables and constrained involved in the ILP formulation is of the order of \( O(L \times P^2) \). Therefore, the complexity of proposed method is lower than the DB method. One can also note that the complexity of the proposed method is same as that of single fault protection method. As evident from the simulation results in the table 1, time to solve the ILP is significantly less for the proposed method. Spare capacity efficiency (SE) is the ratio of spare capacity required for protecting the given working capacity of network see equation (14). Simulation results shows smaller value of SE for most of the networks (see table 1) for the proposed method. Simulation results show that for average nodal degree higher than 3.6, proposed
method gives better SE as can be observed from table 1.

\[ SE = \sum_{i \in S} \frac{s_i}{\sum_{i \in S} w_i} \] (14)

Further, one may note that the proposed method has better restoration speed than DB method. When first failure occur, the failed link is restored as a straddling link. In this way at least half of the copy of p-cycle remains in spare. Restoration path of first failed link does not require rearrangement if, second failure is also a straddling link. If second failure occur on the on-cycle link of p-cycle, only half of the traffic requires restoration. In case of DB method restoration of second failure require switching of traffic from first p-cycle to a different p-cycle.

V. CONCLUSION

From the study, one can conclude that spare capacity requirement for 100% two link failure protection is less for the proposed method as compared to the DB method. ILP of the proposed method is simpler than any other two link failure protection methods. Further, the time required in the ILP formulation and ILP solution are also significantly less.

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