A Comparative Study of Restoration Schemes and Spare Capacity Assignments in Mesh Networks

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***Abstract*— This paper presents the results of a comparative study of spare capacity assignment for original quasi-path restoration (OQPR), improved quasi-path restoration (IQPR), link restoration (LR), path restoration (PR) and link-disjoint path restoration (LDPR) schemes. Numerical results indicate that the restoration schemes studied can be sorted from most expensive to least expensive (spare capacity assignment cost) in the following order: LR, OQPR, IQPR, LDPR and PR. Since IQPR is computationally very efficient, simpler than PR, scalable, and economical in spare capacity assignment, it provides a good alternative to PR when quick restoration is desired. However, due to the potential difficulty in rapid failure isolation coupled with the increasing importance of restoration speed and simplicity, LDPR is an attractive scheme. A number of networks with different topologies and projected traffic demand patterns are used in the experiments to study the effect of various network parameters on spare capacity assignment cost. The experimental analysis shows that network topology, demand patterns and the average number of hops per primary route have a significant impact on the spare capacity assignment cost savings offered by one scheme over the other.**

I. INTRODUCTION

Restoration of disrupted traffic in telecom networks has been studied extensively in literature. We focus on restoration schemes for mesh-type self-healing networks with shared spare capacity. The selection of an appropriate restoration scheme depends on many factors in addition to the spare capacity assignment cost. Some of the important performance criteria are: computational efficiency, restoration speed, complexity, and scalability [1]–[3]. The computational efficiency refers to the processing power and the memory required for the computation. The restoration speed is the time required to restore the disrupted traffic after a failure occurs. Ease of online restoration operation defines the complexity. A good scheme should offer acceptable performance as the network size and the number of demands grow (scalability). Restoration speed is one of the most important performance criterion.

Link restoration (LR) and path restoration (PR) have been widely studied in literature. LR is computationally very efficient, fast, simple, and scalable but expensive in network resources whereas PR is known to be very economical in network resources but computationally very hard and complex. Recently, two new schemes, namely, original quasi-path restoration (OQPR) and improved quasi-path restoration (IQPR) have been proposed [4], [5], which are tradeoffs between LR and PR. These schemes are computationally very efficient, fast, simpler than PR and scalable, which make them good alternatives to PR. This study is aimed at comparing the (offline) spare capacity assignment costs for OQPR and IQPR schemes with LR, PR and link-disjoint path restoration (LDPR). The effect of network parameters on spare capacity assignment cost for theses schemes is analyzed. Merits and demerits of these schemes are also discussed.

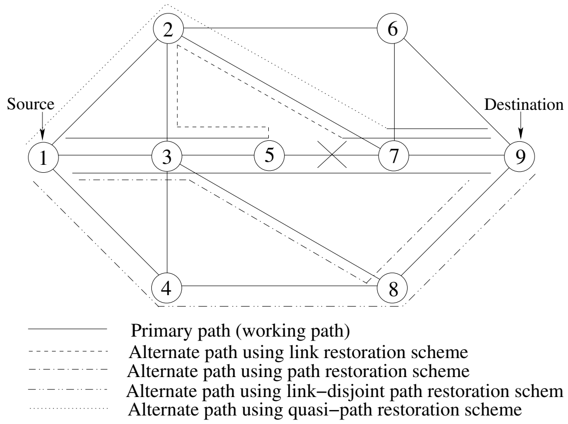

Fig. 1. Alternate paths using LR, PR, LDPR and QPR schemes

II. RESTORATION SCHEMES

A. Link Restoration

LR [3], [6]–[9] reroutes all of the disrupted traffic (going through the failed link) over a single alternate path (or a set of alternate paths) between two end nodes of a failed link, using the spare capacity of the network. In Fig.1, the disrupted traffic (due to the failure of link 5↔7) is rerouted between the end nodes 5 and 7. Thus, the (disrupted) primary path 1-3-5-7-9 has a restoration path 1-3-5-3-2-7-9. The restoration paths found using LR scheme may suffer from *backhauling* i.e. same link being used more than once in a path. As shown in the Fig.1, the restoration route passes through the link 3↔5 twice, resulting in inefficient utilization of the spare capacities. LR is fast because a small part of the network around the failed link has to be reconfigured.

B. Path Restoration

PR [3], [6], [8]–[10] reroutes each disrupted path over a single alternate path (or a set of alternate paths) between the source and the destination of the primary path, using

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the spare capacity of the network. In Fig.1, the (disrupted) primary path 1-3-5-7-9 has a restoration path 1-3-8-9. PR involves finding alternate paths for each disrupted source-destination pair separately. Thus, finding restoration paths using PR scheme is a multi-commodity flow problem, which is NP-complete if the flow values are integers [11]. Because PR can distribute the alternate paths over a wider region of the network, the potential of sharing the spare capacity is high.

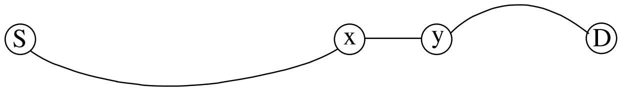
C. Link-disjoint Path Restoration

LDPR [9], [10], [12] is a variation of PR with an additional requirement that alternath path(s) must be link-disjoint to the disrupted path. In Fig.1, the (disrupted) primary path 1-3-5-7-9 has a link-disjoint restoration path 1-4-8-9. The link-disjoint alternate path can be useful as an alternate path for any link failure on the primary path. Restoration can be started immediately after a fault in the path is discovered without waiting to find the faulty link.

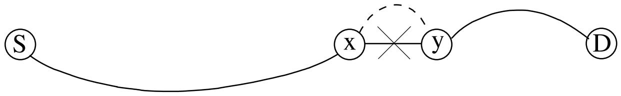
D. Quasi-path Restoration

In quasi-path restoration (QPR), two end nodes connecting a failed link are called *critical nodes*. Each disrupted path (for example path 1-3-5-7-9 of Fig.1) has three components: the subpath from the source to the critical node on the same side (1-3-5), the failed link (5↔7), and the subpath from the critical node on the destination side to the destination (7-9). In QPR, one of the two subpaths remains intact. The disrupted traffic can be rerouted (over a single alternate path or a set of alternate paths using the spare capacity of a network) either between the source (node 1) and the critical node on the destination side (node 7) or between the critical node on the source side (node 5) and the destination (node 9). Thus, depending on the critical node being selected, a possible restoration path can be 1-3-5-3-8-9 or 1-2-7-9. The subpath from the source (or the destination) to the critical node on the same side, namely, 1-3-5 (or 7-9) will remain intact. There are two variations of QPR scheme known as OQPR [4] and IQPR [5]. In OQPR, all the intact subpaths of the disrupted paths will be on the same side of the failed link. In IQPR, the intact subpaths of the disrupted paths can be on both sides of the failed link. The total traffic restored in IQPR, is sum of the traffic restored between the source (node 1) and the critical node on the destination side (node 7) and between the critical node on the source side (node 5) and the destination (node 9). IQPR is more flexible than OQPR. Note that the restoration path(s) found using OQPR or IQPR may suffer from backhauling. Both (online) schemes have a time complexity of O(n^3) [4], [5] which makes them computationally very efficient. An added advantage of these schemes is the integrality of restored traffic flows. If the spare capacities on the links are integers then OQPR can find restoration paths with integer flow values. If the spare capacities on the links are even integers then IQPR can find restoration paths with integer flow values [13].

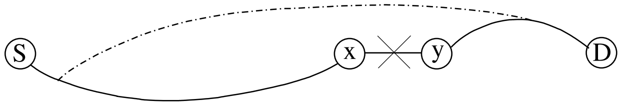
Fig. 2 shows the restoration schemes studied. S denotes the source, D denotes the destination and $x \leftrightarrow y$ denotes a failed link on the primary path from S to D.



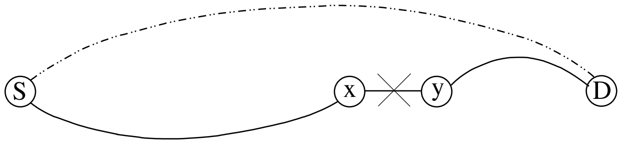
(a) Primary path



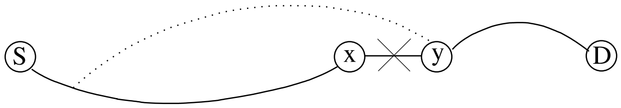
(b) Link restoration



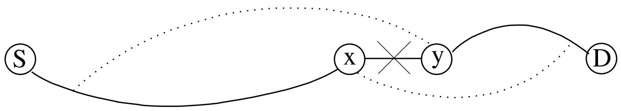
(c) Path restoration



(d) Link−disjoint path restoration



(e) Original quasi−path restoration



(f) Improved quasi−path restoration

Fig. 2. Schametic difference between restoration schemes

III. RELATED WORK

The (offline) spare capacity assignment problem has been formulated as an integer linear program using multi-commodity flow model in [3], [6], [8]–[10], [14]–[18]. These models use pre-defined eligible path sets for all the demand pairs to formulate the search space. The objective is to minimize the cost of spare capacity assignment. The hop limit approach to restrict the path length has been proposed in [14]. The K successively shortest paths approach to restrict the size of the eligible path set is used in [3], [6], [9], [10]. Lagrangian relaxations with sub gradient optimization are used in [1], [19] to simplify the original hard problem. Many innovative schemes and heuristics have been reported in the literature [3], [6], [7], [10], [19]–[21]. A comparison of LR and PR based on the spare capacity cost can be found in [3], [9], [10]. The impact of network topology on the spare capacity requirement for LR and PR has been studied quantitatively in [22].

IV. SYSTEM MODEL

The network under consideration is an undirected graph, forming a mesh network. The nodes are connected through bi-directional links. The nodes are non-faulty and only single link failures are considered. Each link can carry traffic of several different paths. The total traffic carried by each link (when primary routes carry all the point-to-point demands) is called the *working capacity* of the link. The *spare capacity* of a link is the capacity available for restoration in addition to the working capacity.

Let W_j, S_j and C_j denote the working capacity, the spare capacity and the cost of carrying unit traffic on the link j respectively. There are L links in the network. The working capacity cost C_w of the network is defined as $\sum_{j=1}^{L} C_j W_j$ and the spare capacity cost C_s of the network is defined as $\sum_{j=1}^{L} C_j S_j$. The spare capacity cost percentage $SCCP$ of a network is defined as $\frac{C_s}{C_w} * 100$.

V. SPARE CAPACITY ASSIGNMENT

Problem Definition: *Given an undirected network, the cost of carrying unit traffic on each link, a set of point-to-point demands, their primary routes and restoration scheme in a mesh network, find the spare capacity on each link to protect all the demands (100% restoration), which minimizes the total spare capacity assignment cost.*

Two restoration mechanisms are considered:

1) *Split flow* (SF) restoration, where the traffic of a disrupted path can be restored by one or more alternate paths.
2) *Non-split flow* (NSF) restoration, where the traffic of a disrupted path can be restored by only one alternate path.

It is advantageous to release the working capacity occupied by the intact portions of the disrupted primary path so that it can be reused for the restoration. This option is called *stub release* in [9]. (Stub release is not feasible in LR.) Clearly, reusing the released working capacity will reduce spare capacity assignment cost. However, more reconfiguration is required for online restoration and for switching the restored traffic back to its original primary path after the failed link is repaired. The spare capacity allocation problem is studied for both the scenarios, (1) with stub release (-S denotes stub release) and (2) without stub release.

The spare capacities on the links are assumed to be integer variables and the problem is formulated as an integer linear program (ILP). Note that in NSF restoration, if the traffic flows on primary paths are integers then the working and spare capacities on the links and the traffic flows on restoration paths will be integers. Our ILP formulation is similar to the one reported in [6], [9], [10], [14]. Therefore, only the methodology of defining the eligible path set is presented. A *target node pair* is a node pair between which distinct routes are obtained to construct eligible path set for a disrupted path. To achieve the global minimum spare capacity cost, all the possible distinct routes between the target node pair must be represented in the constraint system. The number of all possible distinct routes in networks of moderate size is very large and has been restricted in practice [3], [6], [9], [10], [14]. We have chosen the minimum of K successively shortest loopless paths and all possible loopless paths between the target node pair to form the eligible path set.

In LR, the target node pair consists of the end nodes of the failed link. In QPR, the target node pair consists of the source and the critical node on the destination side or the destination and the critical node on the source side. The criteria used to define target node pairs for OQPR and IQPR are the same as those given in [5], [23]. In PR and LDPR, the target nodes are the sources and the destinations of the disrupted paths.

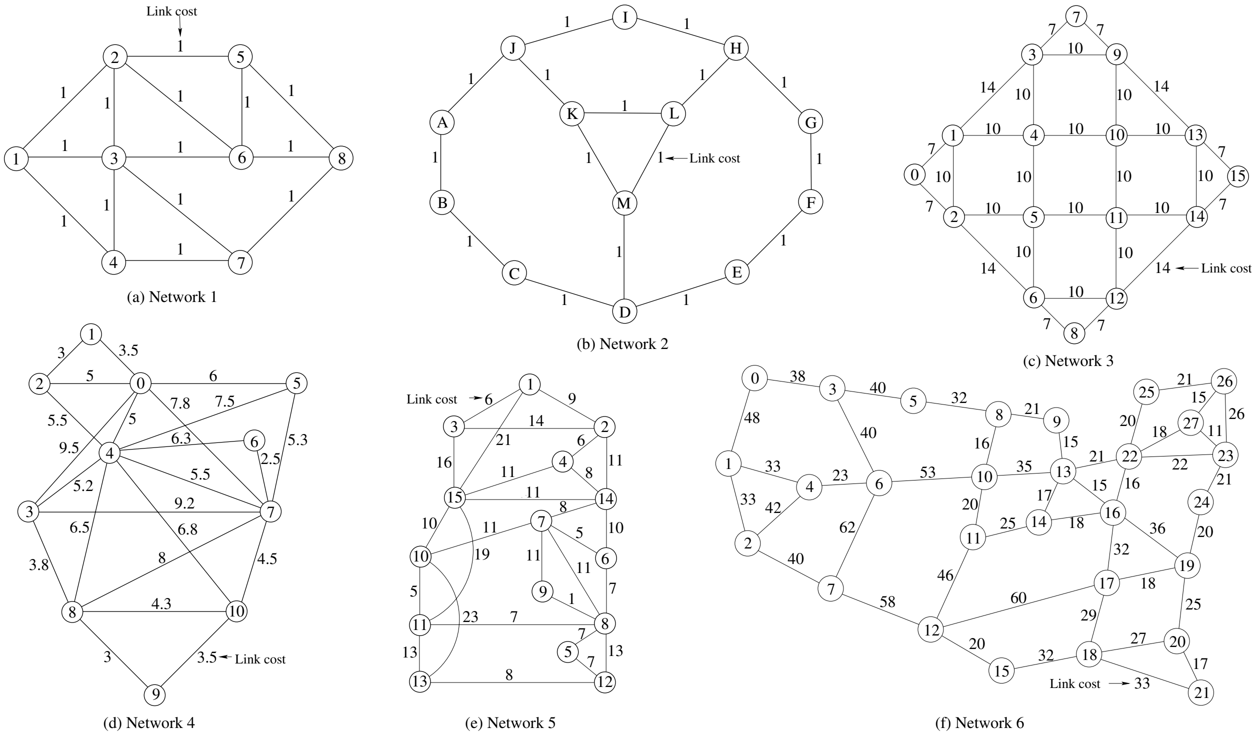
VI. NUMERICAL EXAMPLES

TABLE I
TEST NETWORK CHARACTERISTICS

Net.#	# of nodes	# of links	Avg. degree of a node	# of pt-to-pt demands	Avg. # of hops per demand
1	8	14	3.5	12	2.25
2	13	16	2.4	13	4.07
3	16	28	3.5	44	3.27
4	11	23	4.18	26	2.27
5a	15	28	3.73	68	2.09
5b	15	28	3.73	68	3.21
6a	27	45	3.33	110	1.88
6b	27	45	3.33	110	4.55

Networks Investigated: The six sample networks shown in Fig.3 have been explored in the study. Networks 1, 2 and 3 are artificial networks and networks 4, 5 and 6 are real networks. Networks 3, 4, 5 and 6 have been studied in the literature [3], [22]. The characteristic of each network is detailed in Table I. Non-uniform traffic demands are employed in the experiments. Two sets of point-to-point traffic demands are studied for network 5 and network 6 with different average number of hops per demand. We have named network 5 with two sets of the demands as networks 5a and 5b. Similarly, networks 6a and 6b are named from network 6. The number of shortest loopless paths (K) to construct eligible path set was restricted to 15, 8, 20, 20, 30 and 40 for networks 1, 2, 3, 4, 5 and 6 respectively.

For the given topology and link costs, the value of $SCCP$ is significantly influenced by traffic pattern. The $SCCP$ values reported in this study are for quantitative comparison of restoration schemes, and they will change if traffic patterns are changed. We observed that the NSF restoration problem is very hard to solve. For the topologies and demand patterns of network 3 to network 6, CPLEX [24] was not able to solve the problem to optimality in a reasonable amount of time. In case of SF restoration, computational efforts depend on problem formulation. We examined three different formulations. 1) The spare capacity and flow variables are integer variables. 2) The spare capacity variables are integers and flow variables are continuous variables. 3) The spare capacity and flow variables are continuous variables. All three formulations gave (almost) the same value of $SCCP$ for all the networks investigated. (The maximum variation in $SCCP$ was 0.5%.) The computational time was significantly reduced by relaxing integer variables to continuous variables. For example, PR (without stub release) for network 3, could not be solved using formulation 1 due to memory and time limitation but it was solved in 1.21 seconds using formulation 2 and in 0.35 seconds using formulation 3. All the results reported in the next section were obtained using formulation 2.



(a) Network 1

(b) Network 2

(c) Network 3

(d) Network 4

(e) Network 5

(f) Network 6

Fig. 3. Test Networks

TABLE II

COMPARISON OF RESTORATION SCHEMES IN TERMS OF $SCCP$ FOR SPLIT FLOW RESTORATION

Net.#	LR	OQPR	OQPR-S	IQPR	IQPR-S	LDPR	LDPR-S	PR	PR-S
1	78.70	72.80	72.27	60.24	56.43	61.73	58.52	60.69	56.43
2	104.67	95.25	95.21	83.60	76.46	80.28	78.29	74.19	72.08
3	52.55	48.31	48.09	41.76	37.36	40.05	36.60	37.82	35.54
4	53.25	50.56	50.56	49.84	49.84	49.84	49.84	49.84	49.84
5a	61.66	54.83	54.83	50.54	49.17	49.91	48.06	49.91	47.83
5b	53.99	48.50	48.44	44.43	41.37	41.48	38.33	41.45	38.26
6a	72.68	66.63	66.33	61.29	55.57	58.37	54.75	59.32	55.56
6b	78.56	73.55	73.53	62.75	59.34	53.14	51.78	54.47	52.62

TABLE III

COMPARISON OF $SCCP$ FOR NON-SPLIT FLOW RESTORATION V/S $SCCP$ FOR SPLIT FLOW RESTORATION

Net. #	LR		OQPR		OQPR-S		IQPR		IQPR-S		LDPR		LDPS-S		PR		PR-S	
	SF	NSF -SF	SF	NSF -SF	SF	NSF -SF	SF	NSF -SF	SF	NSF -SF	SF	NSF -SF	SF	NSF -SF	SF	NSF -SF	SF	NSF -SF
1	78.70	6.80	72.80	3.13	72.27	3.37	60.24	8.30	56.43	7.62	61.73	6.88	58.52	6.20	60.69	7.70	56.43	7.62
2	104.67	1.98	95.25	0.12	95.21	0.0	83.60	1.22	76.46	0.16	80.28	0.61	78.29	0.53	74.19	2.44	72.08	0.45

VII. RESULTS AND DISCUSSION

Table II shows the $SCCP$ for SF restoration. Table III shows the comparison of $SCCP$ between NSF and SF restoration. Clearly, SF restoration requires less spare capacity than NSF restoration because it has higher scope of sharing spare capacities. The difference in $SCCP$ between NSF restoration and SF restoration (indicated by NSF-SF in Table III) varies from 0.0% to 8.3%. The difference is smaller in a sparse network (network 2) than in a relatively dense network (network 1) because sparse topology has limited alternatives for the disrupted paths whereas dense topology has many alternatives.

The restoration schemes studied can be sorted in increasing order of flexibility as follows: LR, OQPR, IQPR, LDPR and PR. From Table IV and Table V it is clear that more flexible the scheme, less is the spare capacity assignment cost. LR is the least economical and PR is the most economical restoration scheme. OQPR and IQPR bridge the gap between LR and PR. The $SCCP$ of IQPR is close to that of PR which makes IQPR an attractive scheme. Observe that the difference in $SCCP$ is more in sparse networks than in dense networks. The difference in $SCCP$ is the highest for network 2 (sparse network) and is the lowest for network 4 (dense network). Sparse networks have fewer alternatives for the disrupted path

TABLE IV

$SCCP$ FOR SPLIT FLOW RESTORATION WITHOUT STUB RELEASE

Net. #	LR	LR-OQPR	OQPR-IQPR	IQPR-LDPR	LDPR-PR
1	78.70	5.90	12.56	-1.49	1.05
2	104.67	9.42	11.65	3.33	6.09
3	52.55	4.25	6.54	1.71	2.23
4	53.25	2.69	0.73	0.00	0.00
5a	61.66	6.83	4.29	0.63	0.00
5b	53.99	5.49	4.07	2.96	0.03
6a	72.68	6.05	5.33	2.92	-0.95
6b	78.56	5.02	10.79	9.61	-1.33

TABLE V

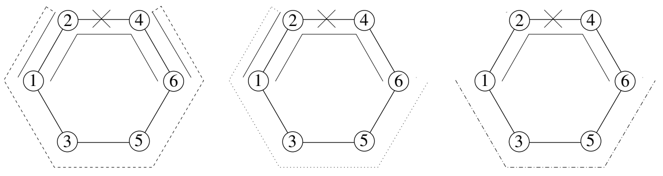
$SCCP$ FOR SPLIT FLOW RESTORATION WITH STUB RELEASE

Net. #	LR	LR-(OQPR-S)	(OQPR-S)-(IQPR-S)	(IQPR-S)-(LDPR-S)	(LDPR-S)-(PR-S)
1	78.70	6.43	15.84	-2.09	2.09
2	104.67	9.46	18.75	-1.83	6.21
3	52.55	4.47	10.73	0.77	1.05
4	53.25	2.69	0.73	0.00	0.00
5a	61.66	6.83	5.66	1.11	0.23
5b	53.99	5.55	7.07	3.04	0.07
6a	72.68	6.34	10.77	0.82	-0.81
6b	78.56	5.04	14.18	7.56	-0.84

than dense networks. There is a greater chance of backhauling in sparse networks than in dense netwoks. (See Fig. 4 and Fig. 5.) Also, LR has the highest chances of backhauling followed by OQPR followed by IQPR. Clearly, network topology has a significant impact on the savings offered by more flexible schemes over less flexible schemes.

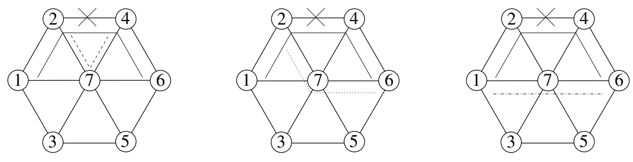
Table II shows that stub release results in reduced $SCCP$ for all the restoration schemes. The savings in $SCCP$ due to stub release range from 0% to 7%. IQPR offers more savings from stub release than OQPR because OQPR is close to LR whereas IQPR is close to PR.

Simulation results (Table II) show that $SCCP$ for LDPR is equal to or more than SCCP for PR for all the networks except for network 6. The link-disjoint candidate paths are subset of all possible candidate paths. The optimal solution for LDPR is also a solution for PR but not necessarily the optimum. The anomaly in the results of network 6 is the consequence of restricting K=40 for a large network. For the same value of K, the eligible path set for PR includes a smaller fraction of all possible distinct paths whereas the eligible path set for LDPR includes a (comparatively) larger fraction of all possible link-disjoint paths. The solution is more likely to be close to the global minimum when ILP searches a proportionally larger area of the solution space. Therefore, the minimum cost solutions for LDPRs are more likely to be closer to the global optimum than corresponding solutions for PR. In PR, most of the candidate paths will share the links with the disrupted path and will be in the close vicinity of the disrupted path. LDPR will allow the long diverse paths in the eligible path set and cover a wider region of the network. Thus, for the small value of K, LDPR will result in a better spread of the spare capacity and lower $SCCP$ than PR. If the value of K increases, then the difference between LDPR and PR decreases and, beyond a certain threshold value of K, PR requires smaller $SCCP$ than LDPR. Similar trends were observed for the networks 1 to 5.



(a) Link restoration (b) Quasi−path restoration (a) Path restoration

Fig. 4. Alternate paths in a sparse network



(a) Link restoration (b) Quasi−path restoration (a) Path restoration

Fig. 5. Alternate paths in a dense network

Note that for networks 1 and 2, IQPR requires lower $SCCP$ than LDPR. Network 1 is very small and network 2 is very sparse. Both networks have very limited number of link-disjoint candidate paths for the disrupted paths resulting in higher value of $SCCP$ for LDPR than those for IQPR.

Interestingly, for network 1, the $SCCP$ for IQPR (without stub release) is less than that for PR (without stub release). The roots of this anomaly lie in the definition of the candidate routes for IQPR. In QPR, a portion of the primary path (beyond the target node pair) remains intact and is not included in the candidate path. Thus, an alternate path in QPR does not require spare capacity on the intact sup-path. If an alternate path in PR (without stub release) takes the same route as an alternate path of QPR, then alternate path in PR will consume spare capacity on the intact sub-path portion of QPR. This makes PR more expensive than QPR in a few cases. With an increase in network size and the demand pairs, this anomaly disappears.

Another important factor contributing to the savings is the average number of hops per primary path. If the average number of hops a primary route traverses is large, more diverse paths are available in the eligible path set of more flexible schemes. Hence, there is more potential for sharing the spare capacity, resulting in lower $SCCP$ for more flexible schemes. If the average number of hops is small, there is little difference between the eligible path set of the less flexible schemes and

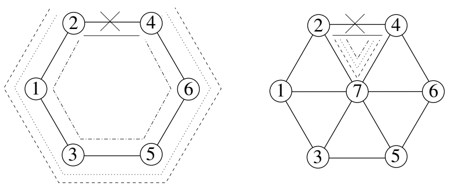


Fig. 6. Alternate paths are the same for all the schemes

the more flexible schemes resulting in small difference in the $SCCP$ of schemes. In Fig. 6 the restoration routes are the same for all the restoration schemes. The spare capacity assignment cost will be identical for all the schemes if all the primary routes are single hop paths. Simulation results confirm this reasoning. Networks 5a and 5b have the same topology, link cost model, and number of demand pairs but, average number of hops per demand pair has increased from 2.09 in network 5a to 3.21 in network 5b. Correspondingly, the savings offered by more flexible schemes over less flexible schemes have increased in networks 5b over 5a. Much greater increase in savings is found in network 6b over 6a, because the number of hops per primary route has also increased significantly from 1.88 in network 6a to 4.55 in network 6b. In the small dense network, the average number of hops per primary path will be very small. This means the resulting savings can be marginal(e.g. network 4).

The study reveals that IQPR, which is computationally very efficient, has an economical spare capacity assignment cost, making it an attractive scheme. LR, OQPR, IQPR and PR need to know which link has failed to start the restoration process. However, it may be time-consuming to determine exactly which link has failed. It is easier for destination to discover a path fault (destination stops receiving signals). LDPR does not need to know which link has failed, so the restoration can be started as soon as the path fault is discovered.

VIII. SUMMARY AND CONCLUSION

An extensive study on the spare capacity assignment cost for LR, OQPR, IQPR, LDPR and PR schemes has been presented and their relative performance is discussed. Our study shows that the savings from SF restoration over NSF restoration are higher in dense networks than in sparse networks at the cost of complexity of online restoration. Stub release offers additional economical gain for all the restoration schemes. The savings are higher in large sparse networks than in dense networks. Besides network topology, the average number of hops the primary path traverses has a significant impact on the savings offered. The restoration schemes studied can be sorted from most expensive to least expensive in the following order: LR, OQPR, IQPR, LDPR and PR. IQPR is a trade off between LR and PR and is a good alternative to PR when quick restoration of the disrupted traffic is desired. However, due to potential difficulty in rapid failure isolation combined with increasing importance of the restoration speed and the simplicity of control, LDPR is a very attractive scheme.

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