Optimal Assignment of Pre Cross-connected Trails to Shared-Backup Path-Protection Resources

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Abstract – This paper addresses a generic task for assigning pre cross-connected backup paths (trails) to shared-backup path-protection resources. We assume that a multi-service network environment, through which common network resources support a given set of services with multiple protection qualities, dictates the boundary conditions for that task. The terms of "donor" and "beneficiary" Pre Cross-connected Trails (PXTs) are defined. A distinction between "path-beneficiary" and "cycle-beneficiary" PXTs is introduced to clarify main considerations of PXT assignment. An ILP model that maximizes the PXT Ratio is developed and fully detailed. Several test networks are analyzed to present some typical results and valuable findings.

I. INTRODUCTION

The main reason for the establishment of Multi-Service Networks (MSNs) is to attain cost savings through "converged" networks, e.g. see [11]. Avoiding service disruptions in such a network environment, despite failure events, requires using a variety of recovery types and their recovery mechanisms, each of which dictates to a large extent the amount of resources assigned and speed of recovery. Selecting a single recovery type for all services in an MSN environment may lead to mismatch situations, such as over-generous network resources for some services and unsatisfactory speed of recovery for others.

In this paper we focus on end-to-end (E2E) path-level recovery rather than line-based recovery. Recovery at the path level is usually more efficient in terms of utilization of network resources, but requires a broader network view when compared to line-based recovery.

The main path-based recovery schemes are:

1 Traditional hot-standby backup paths, called 1+1 with Automatic Protection Switching (APS). This recovery ensures very-short disruption times following the pre-assignment of double E2E paths that are diversely routed to back each other up, clearly quite a dear network solution;

2 Shared Backup Path Protection (SBPP). Compared to 1+1 APS at the path level which uses dedicated backup resources, the backup resources here are shared. As a result, higher resource utilization levels can be achieved but speed of recovery is slower. Capture of shared network resources along pre-determined failure-independent backup paths and reconfiguration at intermediate network elements affect speed of recovery. SBPP is defined as an IETF Internet Draft [8]. Despite that, it has been adopted as a generic, technology-independent, recovery.

3 Pre Cross-connected Trails (PXTs). This term has recently been used for fast path-based recovery [2]. The goal is to stay as close as possible to the efficiency of SBPPs and the speed of 1+1 APS. The first effort in this direction has been developed within the concept of *p*-Cycles, applied to line [4] and recently to path-based [9] levels. The concept of *p*-Cycles ensures full pre-cross-connection solutions. Analysis of disruption times associated with the mentioned recoveries is detailed in [1]. The discussion associated with Figure 4 in this paper further refers to the *p*-Cycles approach.

4 E2E Split Flows. Assignment of E2E split flows can reach some safety margins on service disruptions by maintaining E2E connections despite failure events. A practical use of this recovery relies on Virtual Concatenation (VCAT) combined with the Link Capacity Adjustment Scheme (LCAS). The amount of flow splits is subject to predetermined VCAT Group (VCG) values (selecting VCG >=2).

The Origin-Destination (OD) Cycles is a novel approach for survivability in an MSN environment [5]. The approach adopts an E2E path-based recovery and simultaneously supports 1+1 APS, SBPP and Split Flows, relying on a single optimization process for resource assignment [6].

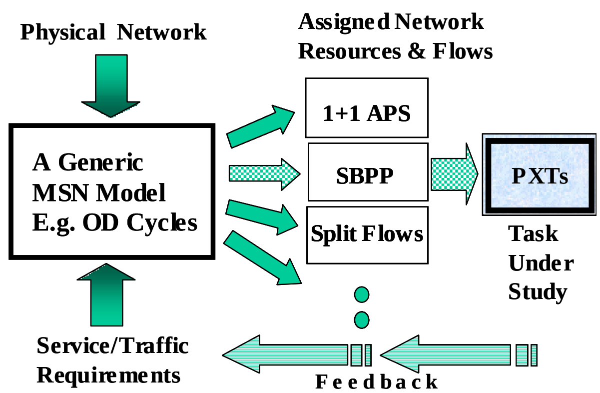

Figure 1 – Framework including PXT assignment

Figure 1 presents a general framework for survivability planning that integrates all recovery types mentioned with the possible use of partial PXT solutions. Future new recovery types may also be included.

We assume that an MSN model dictates overall network resources and the amount of flows assigned to satisfy traffic requirements for the various services. SBPP and PXT recovery types are related by their use of common network resources. The task under study considers assigning PXTs to these common resources in an optimal way. The motivation for this challenge stems from the logical assumption that recovery times for PXTs are naturally less than for general SBPP solutions.

The justification for the framework presented is pure economic as the overall optimal-network cost is supplied by a single-computational model solution. Evaluating the outputs from both the MSN network model and the PXT assignment task may be used as feedback in order to re-consider service/traffic requirements and to answer various "What if …?" scenario questions.

It is important to note that even though there is room for other views on MSN survivability planning, the task under study is valuable on its own merits as results derived from PXTs analysis can still be utilized under different approaches of survivability planning in an MSN environment.

<u>Previous work:</u>

Beyond the cited studies in the area of *p*-Cycles, PXT aspects have captured the attention of others. Recent PXT studies related to mesh-type networks can be found in [2], [7]. The heuristic scheme suggested in [7] introduces the "no-branch-point" necessary condition to a complete PXT solution. The inter-relationship between SBPP and PXT solutions can be summarized as follows: (i) Every complete PXT solution is also an SBPP solution, but not necessarily vice versa; (ii) an SBPP solution is typically more cost effective than a complete PXT solution; in any case it cannot be less cost effective. Complementary issues can also be found in a very recent Ph.D. dissertation [10] dealing with Failure Independent Path Protection (FIPP) *p*-Cycles and transport fundamentals.

Viewing Figure 1 once again, it is clear that the PXT solution derived may not be complete. Carrying out the task under study in an optimal way enables reaching a solution that only maximizes the amount of PXTs and consequently the PXT Ratio by best utilizing the shared resources of a given cost-effective SBPP solution.

The remainder of the paper is organized as follows: Section II clarifies various terms associated with the task under study; Section III details an ILP model to carry out that task in an optimal fashion; Section IV presents typical results obtained from the analysis of three test networks. We conclude with a short summary.

II. ASSIGNING PXTs to SBPP RESOURCES

In this section we clarify the main considerations associated with PXT analysis. For the sake of simplicity we refer to bidirectional E2E capacity units and trails, even though the principles used are also valid for unidirectional situations. It is assumed that a given SBPP solution supplies the following information:

1 Detailed OD working and shared-backup paths.
2 Amount of resources assigned to each OD pair in order to satisfy SBPP recovery requirements.
3 Total amount of shared resources allocated to each network link for SBPP recovery purposes.

Figure 2 presents a simple example of the above information and its impact on PXTs. The pairs <u>AC</u> and <u>BC</u> are assigned working resources of 2 and 3, respectively, along their direct connecting links (total demand for SBPP recovery is 3+2=5). Shared backup resources are assigned to backup paths via D (underlined figures) to cope with any single-network failure. For example, if link B-C is under failure conditions, the three shared backup resources along links B-D and C-D can back up the three working capacities of pair <u>BC</u> by cross-connecting the backup resources at node D. The assignment of PXTs to the shared backup resources is indicated by the figures in *Italics*. It can be seen that a total of three PXTs are assigned, reflecting a PXT Ratio of 60% (total assigned PXTs is 3; total demand is 5).

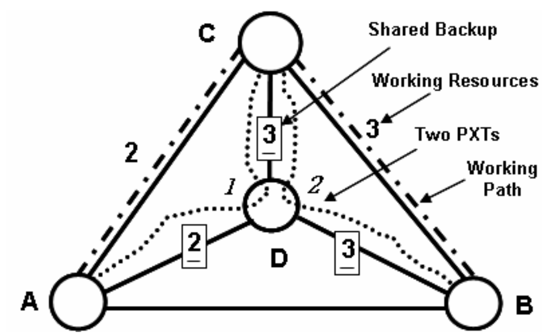

Figure 2 – Basic PXT considerations

Other assignments that maintain the PXT Ratio of 60% are possible, such as: (0 and 3) and (2 and 1) along backup paths (A-D-C and B-D-C), respectively. However, the PXT assignment as indicated in Figure 2 reaches a higher level of fairness compared to the two other cases mentioned. PXT ratio of 50% and 66.7% for OD pairs <u>AC</u> (1 out of 2) and <u>BC</u> (2 out of 3), respectively, are reached. The issue of fairness is part of the PXT assignment model detailed in Section III.

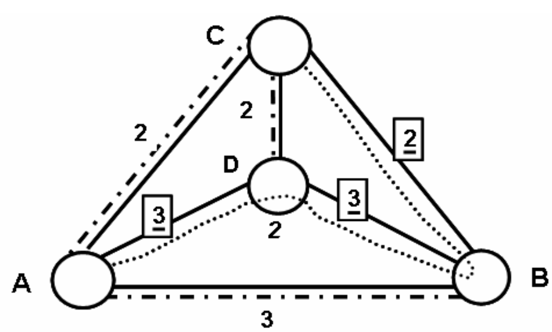

Figure 3 – Donor and beneficiary PXTs

Figure 3 explains further PXT considerations. It is assumed that the figure represents part of a large network. We further assume that the given SBPP solution indicates that the pairs AB, AC and CD are assigned shared backup resources along the failure-independent protection paths A-D-B, A-D-B-C and D-B-C, respectively, while their associated working paths are A-B, A-C and C-D, respectively. It should be noted that this SBPP solution may partly be derived from global cost-effective network aspects that cannot be directly revealed by Figure 3.

Figure 3 presents a PXT along the recovery path A-D-B-C for the pair AC. It can be observed that such a PXT may also serve as a legal backup PXT for the two other pairs AB and CD. In this case the established backup PXT for pair AC is regarded as the "donor", while the associated "beneficiary" PXTs are A-D-B and D-B-C for the pairs AB and CD, respectively. The donor-beneficiary relationship is basically valid under two network conditions:
(i) The beneficiary PXT is part of the donor PXT;
(ii) Their associated working paths do not simultaneously use that PXT following any single network failure.

Condition (i) avoids the creation of "branch points", termed by [2]. Condition (ii) can be fulfilled when the associated working paths are disjoint but not necessarily completely so. Working paths of pairs AC and CD have, for example, the common node C. Failure of node C does not require using the aforementioned PXT, as recovery of the affected working paths is anyhow impossible. From the above, the associated working paths must be both link disjoint and without an intermediate node in common. A donor PXT may contribute to several beneficiary PXTs if they fulfill the two conditions mentioned. If the two beneficiary PXTs share a common link, their associated working paths should be link disjoint.

Figure 4 illustrates additional considerations of the task under study. Three working paths are highlighted for the pairs AH, BD, and DF. We assume that the shared backup paths are established along the cycle A-B…-I-A.

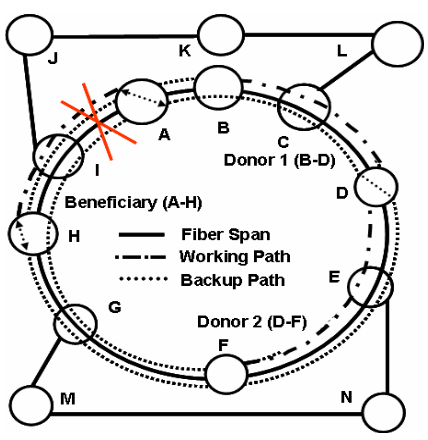

Figure 4 – Use of a cycle-beneficiary PXT

Consider two donor PXTs for the pairs BD and DF. For this particular situation there are no beneficiary PXTs, as defined by the example in Figure 3.

An immediate question arises: Is there any way to utilize the two established donor PXTs as presented in Figure 4?

The union of these two PXTs forms a complete cycle with shared-backup resources. That cycle does not have any branching points if preconfigured at node D, which is common to the working paths of the two donor PXTs. More specifically, that cycle is regarded as a *p*-Cycle that can be utilized for beneficiary PXT purposes.
The donor-beneficiary relationship can apply to this case under three network conditions:
(i) Working and backup paths of a beneficiary PXT are completely within that cycle.
(ii) There is no simultaneous use of PXT resources following any single-network failure (all associated working paths have to be link disjoint).
(iii) The two donor PXTs have a common node to avoid branching.
We use the terms Cycle Beneficiary PXT (CB-PXT) and Path Beneficiary PXT (PB-PXT) to reflect the situations where a beneficiary PXT utilizes the cycle of two donor PXTs and the path of a single donor PXT, respectively.

Consider that CB-PXT of AH is under failure conditions (fiber cut of link A-I). In such a case, the termination nodes A and H are reconfigured as indicated to gain benefit from the two backup paths associated with the donor PXTs. Under such conditions, the requirement to rely only on the termination nodes and not on intermediate nodes (node D in our case), is kept. Under failure conditions associated with each of the two donor working paths, the node D (which for these cases is a termination node) is reconfigured. On the other hand, the nodes A and H are pre-cross-connected to allow the backup paths of the donor PXTs to pass through.

CB-PXTs are expected to appear frequently in sparse networks, while PB-PXTs are typical in dense networks.

III. PXT ASSIGNMENT MODEL

In this section we detail an Integer Linear Programming (ILP) model that maximizes total amount of PXTs, using the following notation:

Model Sets and Parameters:

L	Number of network links, indexed *i=1,2,..,L.*
N	Number of network nodes, indexed *n=1,..,N.*
J	Number of OD pairs associated with SBPP recovery, indexed *j=1,..,J<=N*(N-1)/2.*
R_j	Number of SBPPs associated with the pair *j*, appearing in the SBPP solution, *j=1,..,J*, *r=1,..,* R_j >=1. The SBPP solution also supplies the disjoint working path associated with each BSPP.
PXT	Each PXT is associated with two indexes, OD pair and its serial path number. For the sake of simplicity we use *(j,r)* for donor PXTs and *(m,q)* for beneficiary PXTs, *m,j= 1,2,..,J*, r=1,2,. R_j , q=1,2,.., R_m . SBPP *(j,r)* refers to the *r*-th SBPP of the pair *j*.
T_{jr}	Positive traffic flow supplied by the SBPP solution along the SBPP *(j,r)*, *j=1,..,J*, *r=1,..,* R_j .

TT_j Total traffic associated with pair *j*, *j=1,..,J* that requires SBPP recovery.

Clearly $\sum_{r=1}^{R_j} T_{jr} = TT_j$

TT Total traffic that requires SBPP recovery in the network. This value is in fact the upper bound for the total amount of PXTs that can be assigned due to the given SBPP solution.

Clearly $\sum_{j=1}^{J} \sum_{r=1}^{R_j} T_{jr} = TT$

α_{jr}^{mq} A binary coefficient, gets the value "1" if the beneficiary PXT *(m,q)* may have path benefit from the potential donor PXT *(j,r)* and "0" otherwise. We use $\alpha_{jr}^{jr} \equiv 1$.

$\beta_{j1r1,j2r2}^{mq}$ A binary coefficient, gets the value "1" if the beneficiary PXT *(m,q)* may have cycle benefit from the potential donor PXTs *(j1,r1)*, *(j2,r2)* and "0" otherwise, introducing the condition M*j1+r1<M*j2+r2, where M is a large number, so as to avoid duplication of coefficients..

K_{j1r1}^{j2r2} Amount of donor PXTs that can be established for cycle benefit using SBPPs *(j1,r1), (j2,r2)*.

$$K_{j1r1}^{j2r2} = Min\{T_{j1r1}, T_{j2r2}\}$$

δ_{jr}^{i} A binary coefficient, gets the value "1" if link i is part of the SBPP related to donor PXT *(j,r)* and "0" otherwise, $i = 1,.., L$.

S_i Total shared resources assigned to link *i*, *i=1,2,..,L* as supplied by the SBPP solution.

Pmin A planning parameter, minimal portion of PXTs to be assigned to each pair over all its possible SBPPs. Clearly: $0 \le Pmin \le 1$.

Model Variables:

$V_{jr,k}^{jr}$ A decision (binary) variable about the establishment of a donor PXT *(r,j)* that consumes the *k*-th flow unit along SBPP *(j,r)*, *j=1,..,J, r=1,..,* R_j, *k=1,2,..,* T_{jr} .

$V_{jr,k}^{mq}$ A decision variable about the establishment of a beneficiary PXT *(m,q)*, relying on the donor PXT *(j,r)* and the *k*-th flow unit of SBPP *(j,r)*, *k=1,2,..,* T_{jr} . The purpose in this case is to reach the path benefit.

$U_{j1r1,j2r2,k}^{mq}$ A decision variable about the establishment of a beneficiary PXT *(m,q)*, relying on the donor PXTs *(j1,r1),(j2,r2)* and the *k*-th flow unit along a *p*-cycle following the union of SBPPs *(j1,r1),(j2,r2)*, *k=1,2,.,* K_{j1r1}^{j2r2} . The purpose in this case is to reach the cycle benefit.

F_{mq} Total assigned PXTs along the SBPP *(m,q)*.

B_i Total backup resources assigned to link *i*, following the establishment of all donor PXTs, *i=1,2,..,L* in the network.

Based on the above, the following model is formulated:

Integer-Programming Formulation:

$$Max\{ \sum_{j=1}^{J}\sum_{r=1}^{R_j}\sum_{k=1}^{T_{jr}}\sum_{m=1}^{J}\sum_{q=1}^{R_m} \alpha_{jr}^{mq}\cdot V_{jr,k}^{mq} \; + $$

$$\sum_{j1=1}^{J}\sum_{r1=1}^{R_{j1}}\sum_{j2=1}^{J}\sum_{r2=1}^{R_{j2}}\sum_{k=1}^{K_{j1r1}^{j2r2}}\sum_{m=1}^{J}\sum_{q=1}^{R_m} \beta_{j1r1,j2r2}^{mq}\cdot U_{j1r1,j2r2,k}^{mq} \}$$

S.t

$$V_{jr,k}^{mq} \le V_{jr,k}^{jr} \qquad \forall (j,r),(m,q), \;\; k=1,..,T_{jr} \qquad (1)$$

$$U_{jr,j2r2,k}^{mq} \le V_{jr,k}^{jr} \qquad \forall (j,r),(m,q), \;\; k=1,..,K_{jr}^{j2r2} \qquad (2)$$

$$U_{j1r1,jr,k}^{mq} \le V_{jr,k}^{jr} \qquad \forall (j,r),(m,q), \;\; k=1,..,K_{jr}^{j1r1} \qquad (3)$$

$$U_{jr,j2r2,k}^{mq} + V_{jr,k}^{mq} \le 1 \quad \forall (m,q)^*, k=1,..,K_{jr}^{j2r2} \qquad (4)$$

(* see explanation)

$$U_{j1r1,jr,k}^{mq} + V_{jr,k}^{mq} \le 1 \quad \forall (m,q)^*, k=1,..,K_{jr}^{j1r1} \qquad (5)$$

$$V_{jr,k}^{m1q1} + V_{jr,k}^{m2q2} \le 1 \quad \forall (m1,q1)^{**}(m2,q2), k=1,..,T_{jr} \qquad (6)$$

(** see explanation)

$$U_{j1r1,j2r2,k}^{m1q1} + U_{j1r1,j2r2,k}^{m2q2} \le 1 \quad \forall (m,q)^{**}, k=1,..,K_{j1r1}^{j2r2} \qquad (7)$$

$$\forall (m,q) \qquad \sum_{j=1}^{J}\sum_{r=1}^{R_j}\sum_{k=1}^{T_{jr}} \alpha_{jr}^{mq}\cdot V_{jr,k}^{mq} + \sum_{j1=1}^{J}\sum_{r1=1}^{R_{j1}}\sum_{j2=1}^{J}\sum_{r2=1}^{R_{j2}}\sum_{k=1}^{K_{j1r1}^{j2r2}} \beta_{j1r1,j2r2}^{mq}\cdot U_{j1r1,j2r2,k}^{mq} = F_{mq} \qquad (8)$$

$$F_{mq} \le T_{mq} \qquad \text{if } R_m = 1, \forall m = 1,2,.., J \qquad (9)$$

$$\sum_{j=1}^{J}\sum_{r=1}^{R_j}\sum_{k=1}^{T_{jr}} \delta_{jr}^{i}\cdot V_{jr,k}^{jr} = B_i \;\; \forall i = 1,2,..,L \qquad (10)$$

$$B_i \le S_i \qquad \forall i = 1,2,..,L \qquad (11)$$

$$\text{Pmin}\cdot TT_m \le \sum_{q=1}^{R_m} F_{mq} \le TT_m, \forall m = 1,2,..J \qquad (12)$$

$V_{jr,k}^{mq}, U_{j1r1,j2r2,k}^{mq}$ Binary Variables

F_{mq} , B_i ≥ 0 Integer Variables

The objective function maximizes total PXTs. Optimal PXT Ratio is obtained by simply dividing the objective function presented by the constant value TT (which is total demand for SBPP recovery).

Constraints (1) state that any PB-PXT must rely on a donor PXT in order to utilize path benefit. Similarly, Constraints (2) and (3) ensure that any CB-PXT must rely on two donor PXTs.
Constraints (4) and (5) limit the beneficiary PXT alternatives to a single choice of either a PB-PXT or a CB-PXT (gain cannot be counted twice). Constraints (6) and (7) disallow two beneficiary PXTs to utilize a donor PXT and two donors for PB and CB purposes, respectively, if their working paths are not link disjoint.
Constraints (8) accumulate total PXTs for each demand SBPP *(m,q)* while Constraints (9) limit their amount subject to the SBPP solution. It is worth noting that the Constraints (9) can be less tied when $R_m > 1$ and two or more SBPPs of that OD pair are associated with identical working paths (such information is known from the supplied SBPP solution). For example, if for a certain *m* value R_m =3 and the last two associated SBPPs use the same working path, then a looser constraint could be:

$$F_{m2} + F_{m3} \le T_{m2} + T_{m3} \qquad (9a)$$

Constraints (10) accumulate the resources assigned to each link following the established donor PXTs. Constraints (11) limit the accumulated PXT resources on each link to comply with the boundary conditions dictated by the SBPP solution.
Constraints (12) limit the accumulated PXT resources for each pair to comply with the SBPP solution. In addition, the minimal portion of PXTs for each OD pair, dictated by the fairness parameter *Pmin*, is introduced. *Pmin* values should be selected carefully to avoid infeasible solutions.
Dimensions of the ILP model, in terms of variables and constraints, are dependent not only on network size but also on the supplied SBPP solution. This is particularly true when referring to the CB-PXT considerations.

IV. NUMERICAL RESULTS AND FINDINGS

The ILP model detailed in the previous section is implemented and tested on a T43 IBM machine, using 1Gbytes RAM and the CPLEX 9.0 optimization engine. Figures 5 (a) and 5 (b) present the three test networks used for the analysis.

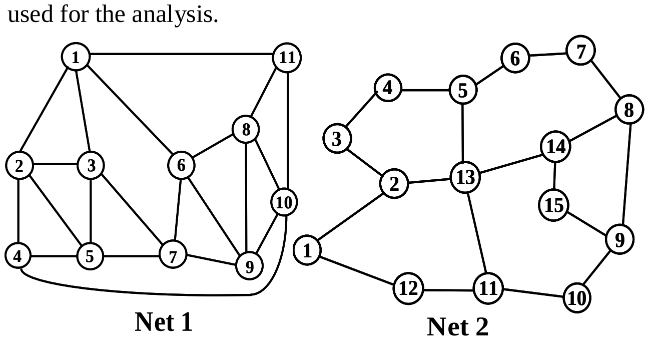

Figure 5 (a) – Networks 1 and 2 used for analysis

Net 1 and Net 2 are different by nature. While Net 1 is a dense network (average nodal connectivity 3.8), used in [6], Net 2 is a sparse network (nodal connectivity 2.5), presented in [3].

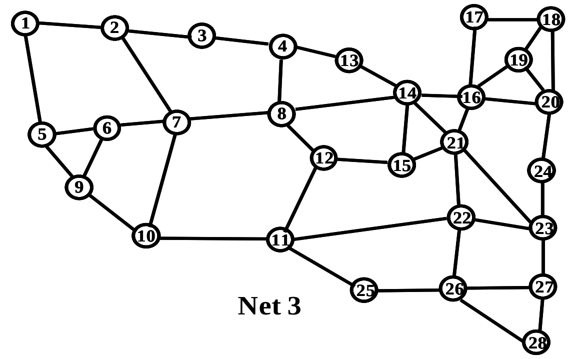

Figure 5 (b) – The US long-haul network tested

Net 3 (28 nodes, 45 fibers, nodal connectivity 3.2) is the well-known US long-haul transport network.
The ILP model was applied to each of the three networks. Four different scenarios were considered, noted as Cases 1-4. As the networks are quite different by nature, a separate discussion is assigned to the results of each network. The model as in [6] is used to supply SBPP solutions for PXT analysis, see Figure 1.

Net 1	Case 1-Path Limit = 1; Case 2 - Path Limit = 2; Case 3-Path Limit = 3; Case 4 - No Path Limit			
Features \ Case	1	2	3	4
SBPP Demand	510	510	510	510
Sum working	916	923	928	931
Sum shared	732	502	490	431
Sum PXTs	249	227	229	227
PXT Ratio (%)	48.8	44.5	44.9	44.5
Donor PXTs	204	124	128	101
PB PXTs	39	97	98	120
CB PXTs	6	6	3	6
Variables	692	833	836	976
Constraints	1,291	1,485	1,453	1,621
CPU Time (Sec)	Secs	Secs	Secs	Secs
Pmin=0.2 Sum PXTs	232	211	205	215
PXT Ratio (%)	45.5	41.4	40.2	42.6

Table1 – Dense Net 1 results

Table 1 presents results associated with Net 1. The purpose of this analysis is to learn about the impact of path-flow restrictions on PXT results in a dense network, maintaining total SBPP demand unchanged. Cases 1, 2 and 3 represent constrained SBPP solutions, enforcing R_j =1, 2 and 3, respectively, for all pairs *j=1,2,..J*. Case 4 is an unconstrained SBPP solution. PXT analysis investigates the impact of flow bifurcation. Clearly the SBPP solution for Case 4 (Case 1) is more (less) cost effective than the other cases. It can be observed that limiting the number of path-flows overall increases the shared resources. Case 4 therefore uses the lowest level of shared backup resources, as expected.
It can be seen that the path-flow restrictions affect the number of both donors and PB-PXTs but PXT Ratio does not vary significantly. It can also be seen that the contribution of CB-PXTs is very low. This can intuitively

be explained by the very-large number of possible cycles in the dense network which reduces the potential beneficiary PXTs per cycle. Increasing the fairness parameter Pmin from 0 to 0.2 slightly lowers the PXT Ratio for all four cases tested. CPU time to obtain the results is in the order of single seconds.

Net 2	Case 1-- Hub-13; Case 2 -- 1H-Uni10, 2H-Uni5; Case 3-- 30% Rand; Case 4-- 60% Rand			
Features \ Case	1	2	3	4
SBPP Demand	140	319	320	632
Sum working	260	447	876	1,656
Sum shared	267	314	625	1,094
Sum PXTs	76	206	195	474
PXT Ratio (%)	54.3	64.6	60.9	75.0
Donor PXTs	43	47	82	160
PB PXTs	33	21	58	84
CB PXTs	0	138	55	230
Variables	295	1,782	838	2,723
Constraints	576	3,931	2,019	6,683
CPU Time (Sec)	Secs	8	Secs	85
Pmin = 0.2 Sum PXTs	76	184	189	462
PXT Ratio (%)	54.3	57.7	59.1	73.1

Table 2 – Sparse Net 2 results

Table 2 details the results obtained for Net 2. It can immediately be observed that the SBPP solutions consume a significantly higher level of shared resources compared to Net 1 (Sum shared/Sum working is higher) and consequently improve PXT results, as expected.
Traffic distribution in sparse networks has a major impact on working and backup path lengths. The investigation here is to learn the impact on PXTs. Case 1 represents a pure hub traffic directed to the network center (node 13). It can be seen that no CB-PXTs are found. Hub traffic, therefore, not only yields low utilization of network resources (the ratio Sum shared/Sum working is the highest), but also results in low PXT ratio values, realizing that condition (ii) - detailed on page 3 as part of the discussion on Figure 4 - cannot be met. Case 2 assumes that the majority of traffic is between neighbors (1-hop distant) while the rest of the traffic is between 2-hop distant neighbors. Such traffic in a sparse network requires relatively long SBPPs. PB-PXTs are therefore limited, while CB-PXTs are dominant.
Traffic distribution for Cases 3 and 4 is selected randomly, for which 30% and 60% of OD pairs are associated with SBPP traffic, respectively. Case 4, which represents the largest ILP dimensional problem solved, is manageable as CPU time is still quite reasonable. Impact of the fairness parameter is more significant for Case 2.

Table 3 summarizes the results obtained for Net 3. Traffic distribution is selected randomly for all four cases that differ from each other by the amount of OD pairs having survivable traffic. Case 1 and Case 4 supply the smallest and largest dimensional problems, respectively. CPU time is in the range of 29-77 seconds, still quite short despite the large ILP model dimensions.

The PXT Ratio decreases steadily with the increase of traffic and the resource-sharing possibilities (resulting in the steady decrease of Sum shared/Sum working). When selecting *Pmin* = 0.2 for the analysis, no feasible solutions are found for Cases 2-4.

Net 3	Case 1-- 20% Random; Case 2 -- 30% Random; Case 3-- 40% Random; Case 4 -- 50% Random.			
Features \ Case	1	2	3	4
SBPP Demand	1,247	1,880	2,511	3,155
Sum working	4,276	6,524	8,566	10,496
Sum shared	2,844	4,113	5,288	6,470
Sum PXTs	509	690	912	1,102
PXT Ratio (%)	40.8	36.7	36.3	34.9
Donor PXTs	348	440	620	691
PB PXTs	146	228	277	370
CB PXTs	15	22	15	41
Variables	2,083	3,402	3,916	5,099
Constraints	3,694	6,066	7,197	10,257
CPU Time (Sec)	29	31	16	77
Pmin = 0.2 Sum PXTs	451	Infeas.	Infeas.	Infeas.
PXT Ratio (%)	36.2	-	-	-

Table 3 – Net 3 results

SUMMARY

A generic task for assigning pre cross-connected backup trails when using SBPP resources is addressed. An ILP model for this task is developed and tested on typical transport networks. CPU times for solving the ILP model developed are fortunately manageable, despite the large-scale ILP cases that have to be dealt with.
In sparse networks the task performance is satisfactory, reaching PXT solutions in the range of 54-75% with dependency on traffic distribution. PXT assignment for hub traffic distribution is found to be quite problematic, as Cycle-Beneficiary PXTs are not possible.
In dense mesh networks the task performance drops and even becomes infeasible for moderate Pmin fairness values. This calls for further investigation on beneficiary PXT possibilities and this is currently under re-evaluation.

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