Protection Coordination for Dual Failure on Two-Layer Networks

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Abstract—**Network layers such as IP/MPLS and OTN/ASON each has its own failure protection scheme. We propose a coordinated protection plan, so called *protection synergy*, to protect all possible dual failures by utilizing existing single failure protection schemes. There are two aspects essential for effective dual failure protection: One is to guarantee the connectivity under any dual fiber failures, the other is to allocate minimum but enough spare capacity on both layers. Our model achieves both goals using a novel topology mapping technique and computing working and backup paths with an accurate path disjoint criterion. The experimental results on four networks demonstrate complete dual failure restorability and spare capacity savings of the protection synergy approach.**

Keywords—multilayer network survivability; survivable topology mapping; spare capacity allocation; dual failure protection; shared backup path protection; protection and restoration

I. INTRODUCTION

Protection coordination is an important problem in multilayer optimization for IP-over-optical networks, and there is a growing interest in multi-layer resilience [1] [2]. Current backbone networks are built in layers to reduce the complexity over several factors: *Quality of Service* (QoS) guarantee, capital/operational expenditures (CAPEX/OPEX), and the service provisioning speed. While the protection mechanism against single failure might have been well-established in each of these layers, the coordination across layers to protect dual fiber failures has rarely been done.

An earlier work [3] proposed four models for dual-failure protection coordination on two-layer networks. The first model is the only one that can achieve 100% dual failure restorability. However it is in fact a single-layer dual-failure protection scheme on the optical layer alone, and it is very complicated at the time. The other three models have explored coordinated protection across layers, but they are unable to provide 100% dual failure restorability. Our work addresses these limitations and provide coordinated protection with complete dual-failure restorability while still maintaining the minimum spare capacity whenever possible.

Regarding to the difficulty of the first model in [3], we have recently developed a solution to minimize the total shared spare capacity for both 1:1:1 and 1+1:1 *Shared Backup Path Protection* (SBPP) for single-layer dual-link failure in [4]. SBPP allows each flow to have one working path and two pair-wise disjointed backup paths. The shared spare capacity among different backup paths from different flows is computed based on whether these flows have common dual failure scenarios. We show that 1:1:1 SBPP can achieve both full resiliency on dual failure and significant savings on resource redundancy: It can go as low as 98%-180% in 1:1:1, as opposed to 313%-400% in 1+1+1 *Dedicated Backup Path Protection* (DBPP), and 187%-310% in 1+1:1 hybrid of SBPP and DBPP on five networks studied in [4].

There are also works addressing dual failure protection and restoration based on single-failure protection in single-layer networks. Service restorability upon dual failures under these scenarios has been studied in [5][6]. While a span restorable network can enjoy very high (90%) dual-failure restorability [5], an SBPP protected network has significantly lower dual-failure restorability, and reducing backup path sharing could improve this restorability [6].

Our recent work shows that flows are fully restorable on 94-99.7% dual fiber-cut scenarios on four single-failure protected two-layer networks [10]. This result calls for protection coordination across layers for full dual-failure restorability, especially by reusing existing single-failure protection effectively.

We consider protection coordination on IP/MPLS over OTN/ASON where both layers have single failure protection schemes implemented. An IP/MPLS layer link is always carried by a path on the OTN layer in units of ODU*k*, where *k* is between 0 and 4. This OTN path is associated with a list of fibers. For simplicity, the differences between electrical and optical layers within OTN are ignored.

We use inter-layer mapping to capture all packet links supported by the optical (OTN) paths. The inter-layer topology mapping and its equivalent information, *Shared Risk Link Group* (SRLG), have been well studied on multi-layer networks. The correct survivable topology mapping allows the packet layer topology to be resilient to any link failure or fiber cut on the optical layer. This problem has been formulated as an NP-hard model in [7]. Fast approximation algorithms are needed for solving such an inter-layer mapping problem on large networks, e.g. the *Survivable Mapping Algorithm by Ring Trimming* (SMART) in [8] and its further enhancements in [13][14]. Correct and fast survivable topology mapping algorithms allow further cross-layer spare capacity allocation [9]. Our work combines the inter-layer topology mapping and spare capacity allocation for dual-failure restorability while reusing existing single-failure protection and restoration schemes.

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II. PROPOSED PROTECTION SYNERGY APPROACH

A. Assumptions for Protection Synergy

The *protection synergy* approach uses existing protection schemes for single failures on both layers to protect against all dual failures on the optical layer. It computes working and backup paths on both layers in a coordinated way so that services on the packet layer are resilient against dual failures on the optical layer.

Both layers have implemented single failure protection or restoration schemes as follows:

On the optical layer, e.g. OTN, the SBPP is preplanned for the best resource efficiency. Each packet link has two optical paths established. The working optical path carries normal traffic on the packet link and the backup optical path is used only when the corresponding working path fail. The different backup optical paths can share their bandwidth as long as their working paths will not fail at the same time. This can be done due to the assumption of the single failure protection on the optical layer. Our previous work [11] has detailed math programming model and solution approach for this problem.

It is possible to extend this SBPP scheme to the local protection scheme where protection paths are used to detour traffic on failed optical links or nodes, not on the end to end working paths. This local protection is not addressed here, but left for future work.

On the packet layer, i.e. IP/MPLS, the restoration scheme for single failure is considered first. It requires the IP topology to remain connected when any single IP link goes down. This considers the connectivity but not the capacity required for service restoration.

To guarantee full service restoration, the SBPP scheme for all single failures can be considered. In SBPP, each end-to-end LSP might have two explicit routes. The working route is used to carry traffic. The backup route is disjoint from its working route so that traffic on this LSP can be restored once a failure disconnects the working route. Similar to the SBPP on the optical layer, previous work [11] has addressed this problem.

Since MPLS *Fast Reroute* (FRR) is the other well-used local protection framework for single link/node failures, the protection synergy approach for SBPP on this layer is also useful for FRR. FRR might need slightly higher network overbuild than SBPP, but it scales better since it needs per-link or per-node bypass LSPs instead of per-LSP backup routes in SBPP. The scalability drawback of SBPP, on another side, allows the better granularity to provide the class-oriented service survivability using DiffServ-Awared TE on MPLS backbone networks.

For these reasons, the protection synergy will focus on the restoration scheme on packet layer in this paper, SBPP and FRR for future study.

B. Notations

The two-layer network is modeled using the notation in TABLE I. , similar to [9].

The top layer IP/MPLS network is modeled by a directed graph of N nodes, L links, and R flows. Flow r ($1 \leq r \leq R$) may have its origin/destination node pair $(o(r), d(r))$ and traffic demand m_r. Working and backup paths of flow r may be represented by two $1{\times}L$ binary row vectors $p_r = \{p_{rl}\}$ and $q_r = \{q_{rl}\}$ respectively. The l-th element in one of the vectors may be equal to one *if and only if (iff)* the corresponding path uses link l. The path link incidence matrices for working and backup paths may be the collections of these vectors, forming two $R{\times}L$ matrices $P = \{p_{rl}\}$ and $Q = \{q_{rl}\}$ respectively. The diagonal matrix $M = Diag(\{m_r\}_{R\times 1})$ denotes the flow bandwidth. The topology is represented by the node-link incidence matrix $B = (b_{nl})_{N\times L}$ where $b_{nl} = 1$ or -1 *iff* node n is the origin or the destination node of link l. The relation $D = (d_{rn})_{R\times N}$ may be the flow node incidence matrix where $d_{rn} = 1$ or -1 *iff* $o(r) = n$ or $d(r) = n$.

TABLE I. NOTATION

N, L, R, K	Numbers of nodes, links, flows, and failures on the IP/MPLS layer
n, l, r, k	Indices of nodes, links, flows, and failures
$P = \{p_r\} = \{p_{rl}\}$	Working path link incidence matrix
$Q = \{q_r\} = \{q_{rl}\}$	Backup path link incidence matrix
$M = \text{Diag}(\{m_r\})$	Diagonal matrix of bandwidth m_r of flow r
X^b	Any symbol X with a superscript b is considered for the bottom layer
$H = \{h_l\} = \{h_{lj}\}$	Primary mapping matrix from IP links to optical links
$W = \{w_l\} = \{w_{lk}\}$	Secondary mapping matrix from IP links to optical links
$o(r), d(r)$	Origin/destination nodes of flow r
$B = \{b_{nl}\}_{N\times L}$	Node link incidence matrix on the top layer
$D = \{d_{rn}\}_{R\times N}$	Flow node incidence matrix on the top layer
$G = \{g_{lk}\}_{L\times K}$	Spare provision matrix, g_{lk} is spare capacity on link l for failure k
$G_r = \{g_{lk}^r\}_{L\times K}$	Contribution of flow r to G
$s = \{s_l\}_{L\times 1}$	Spare capacity vector
$\phi = \{\phi_l\}_{L\times 1}$	Spare capacity cost function, ignored if the capacity replaces the cost.
W, S	Total working, spare capacity
$\eta = S/W$	Network redundancy
$F = \{f_{kl}\}_{K\times L}$	Failure link incidence matrix, $f_{kl} = 1$ *if and only if (iff)* link l fails in failure scenario k
$U = \{u_{rk}\}_{R\times K}$	Flow failure incidence matrix, $u_{rk} = 1$ *iff* failure scenario k affects flow r's working path
$T = \{t_{rl}\}_{R\times L}$	Flow tabu-link matrix, $t_{rl} = 1$ *iff* link l should not be used on flow r's backup path

In the bottom layer, the notation on the top layer IP/MPLS is reused and the superscript "b" is added for distinction, e.g. the directed graph for the bottom layer has N^b nodes, L^b links, and R^b flows. Without lost of generality, we assume that both layers have the same number of nodes, i.e. $N^b = N$; and the bottom layer's flow number is equal to the number of IP links $R^b = L$. Since a top layer IP link is carried by a bottom layer OTN path, the topology mapping is defined in a matrix $H = \{h_l\} = \{h_{lj}\}_{L\times L^b}$. This matrix is equivalent to the working path matrix on the bottom layer, i.e. $P^b = H$. Meantime, the bottom layer supports the single failure protection using the disjoint backup paths. These disjoint paths can be aggregated into the secondary topology mapping matrix $Q^b = W =$

$\{w_l\} = \{w_{lj}\}_{L\times L^b}$. In the following text, matrices H and W are used for topology mapping related purpose while P^b and Q^b are used for spare capacity allocation and disjoint path computation purposes. They are interchangeable based on related context.

C. *Formulation for Single Failure Resilient SBPP*

Using the above assumption and notation, the single failure protection scheme on the packet layer are described here.

On the top layer, all flows have two disjoint paths represented in two path matrices P and Q. The working paths are computed as the shortest hop paths first, and the backup paths are computed using the *Spare Capacity Allocation* (SCA) model in [11][9]. It is also in (1)-(8) and explained below.

$$\min_{Q,\ s} \quad S = e^T s \tag{1}$$

$$s.t.: \quad s = \max G \tag{2}$$

$$G = Q^T M\, U \tag{3}$$

$$T + Q \ \leq 1 \tag{4}$$

$$QB^T = D \tag{5}$$

$$Q: binary \tag{6}$$

$$U = P \odot F^T \tag{7}$$

$$T = U \odot F \tag{8}$$

This SCA model has the objective to minimize the total spare capacity in (1) with the constraints in (2) to (8). The decision variables are the backup path matrix Q and the spare capacity vector s. The constraints in equations (2) and (3) may associate these variables, i.e., the spare capacity allocation s may be derived from the backup paths in Q. The constraint of equation (4) may guarantee that every backup path does not use any link which may fail simultaneously with any link on its working path. A flow conservation constraint in equation (5) may guarantee that backup paths given in Q are feasible paths of flows in a directed network. The incidence matrices U and T may be pre-computed. The matrix U may indicate the failure cases that influence the working paths. The matrix T may indicate the links that are to be avoided in the backup paths. Both U and T have been used to capture the SRLG-disjoint requirement in [11]. The link load, the traffic flows, and their routes may be symmetric. In a directed network, each link may have two directions with asymmetric load. In computation, the link dimensions will be doubled, i.e. $2L$ in directed instead of L in undirected networks.

In this SCA model, K failure scenarios may be characterized in a binary matrix $F = \{f_k\}_{K\times 1} = \{f_{kl}\}_{K\times L}$. The row vector f_k in F may be for failure scenario k and its element f_{kl} may be equal to one *iff* link l fails in scenario k. In this way, each failure scenario may include a set of one or more links that may fail simultaneously in the scenario. For a failed node, all the node's adjacent links may be marked as failed. A flow failure incidence matrix may be denoted as $U = \{u_r\}_{R\times 1} = \{u_{rk}\}_{R\times K}$, where $u_{rk} = 1$ *iff* flow r is affected by failure k, and $u_{rk} = 0$ otherwise. The flow tabu-link matrix $T = \{t_r\}_{R\times 1} = \{t_{rl}\}_{R\times L}$ may have $t_{rl} = 1$ *iff* the backup path of flow r should not use link l, and $t_{rl} = 0$ otherwise. U and T are computed from P and F, respectively, as shown in equations (7) and (8) below. A Boolean matrix multiplication operation "$\odot$" is used in equations (7) and (8), which is a matrix multiply operator that is similar to normal matrix multiplication except that the general numerical addition $1 + 1 = 2$ is replaced by the Boolean "or" $1 + 1 = 1$. Using this operator, the logical relations among links, paths, and failure scenarios can be simplified into these matrix operations.

The matrix $G = \{g_{lk}\}_{L\times K}$ may denote a spare provision matrix whose elements g_{lk} are the minimum spare capacity required on link l when failure k occurs. The relation $K = L$ may be true when the SCA protects all single link failures. With the backup paths Q, the demand bandwidth matrix M, the working path P, and the failure matrix F, G may be determined by equations (3) and (7). The minimum spare capacity required on each link may be denoted by the column vector $s = \{s_l\}_{L\times 1}$, which may be found in equation (2). The function max() in equation (2) may indicate that an element in s is equal to the maximum element in the corresponding row of G. This may be equivalent to $s \geq G$ in this SCA model. The parameter ϕ_l may denote the cost function of spare capacity on link l. The vector $\phi = \{\phi_l\}_{L\times 1}$ may be a column vector of these cost functions and $\phi(s)$ may give the cost vector of the spare capacities on all links. The total cost of spare capacity in the network may correspond to $e^T\phi(s)$, where e is the unit column vector of size L. For simplicity here, all cost functions $\phi(s)$ may be identity functions, i.e., $\phi(s) = s$. The term e^T corresponds to the transpose of the unit vector e according to the known standard transpose matrix operation. The standard transpose operation $(\cdot)^T$ is also used in other equations.

This SBPP model in (1)-(8) addresses the SRLG-disjoint requirement on the packet layer using the tabu-link matrix T. The protection approach would be quite similar to our previous work in [9] except the failure matrix has been extended from all single fiber cuts to all dual fiber cuts. This could lead to the difficulties on finding the completely SRLG-disjoint backup routes. One option to this difficulty is to use the failure dependent protection, as mentioned in [12]. Another option is to use the partial disjoint paths developed in [16]. The study on these protection schemes on packet layer is left for future work.

An IP link l has two paths on the bottom layer that are link disjoint with each other, i.e. p_{lj}^b and q_{lj}^b, where $1 \leq j \leq L^b$. Similar to the top layer single failure protection scheme, one way to compute these paths using SBPP is to sequentially compute the shortest hop paths as the working paths and then compute link disjoint paths as the backup paths using the SCA model in (1)-(8). The link disjoint constraints can be highlighted in (9) on undirected networks.

$$P^b + Q^b \ \leq 1, \text{ or equivalently, } H + W \ \leq 1 \tag{9}$$

It is important to know that on direct networks, the link-disjoint requirement needs both directions of a link to be used at most once by one of the working and backup paths. To accomplish this, a special failure matrix F_{LF} is assigned to indicate all single link failures, where each failure impacts both directions of a link. Then computing matrices U^b and T^b in (10), similar to (7) and (8), the link disjoint requirement can be enforced in (16), similar to (4).

$$T^b = U^b \odot F_{LF},\ U^b = H \odot F_{LF}^T \tag{10}$$

When the bottom layer has provided the single failure protection scheme, the survivable requirements on the topology mapping H, as specified in (21)-(23) might not be necessary any more, since any single failure can be completely shield inside the bottom layer, as also explained in III-A of [9]. However, this survivable topology mapping requirement is critical to develop the protection synergy for dual failure.

D. Formulation for Protection Synergy

The protection synergy is targeted to provide dual failure protection using existing protection schemes on both layers. Using the dual failure definition in [4], we can capture all dual link failures on the bottom layer in the following.

The total number of dual link failures on the bottom layer may be $K = \binom{L^b}{2} = L^b(L^b-1)/2$, i.e., the number of possible combinations of two optical links. Each failure $k \in 1..K$ may correspond to a pair of failed optical links i, j. The index k may be determined as $k = \sum_{m=L^b-i+1}^{L^b-1} m + (j-i)$ where $1 \le i < j \le L^b$. The failures of two links may happen at about the same time or shortly close to one another so that the impacted IP link will have to depend on the protection scheme on the IP layer. In a dual link failure scenario k, the working and backup paths of IP link l will have to be disconnected together for this IP link to be disconnected. In this case, the bottom layer's flow to failure incidence element u_{lk}^b should be identical to the top layer's failure matrix f_{kl}, defined in (11)

$$f_{kl} = u_{lk}^b = p_{li}^b q_{lj}^b \oplus q_{li}^b p_{lj}^b = h_{li} w_{lj} \oplus w_{li} h_{lj}. \tag{11}$$

Hence, $f_{kl} = u_{lk}^b = 1$ may indicate that dual failure case k breaks the IP link l because it will disconnect both of the working and backup optical paths p_l^b and q_l^b (or h_l and w_l) simultaneously. This may indicate that the dual link failure k

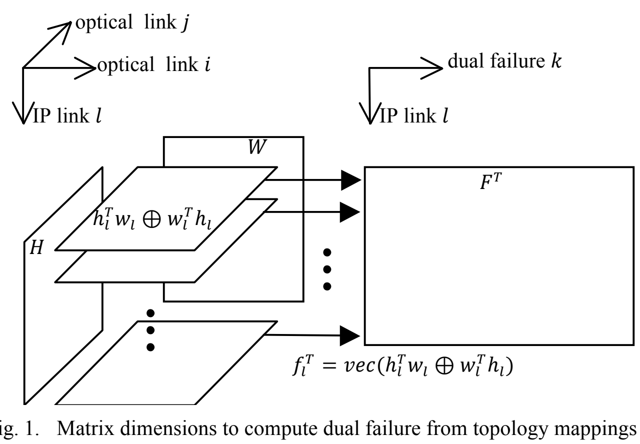

Fig. 1. Matrix dimensions to compute dual failure from topology mappings

on the bottom layer could also disconnect IP link l, the concept of the SRLG caused by dual failures. The aggregation of all dual failures will then turn into the vector for a specific IP link in (12) and the overall failure matrix in (13). The matrix dimensions are illustrated in Fig. 1.

$$f_l^T = \{f_{lk}\} = \text{vec}(h_l^T w_l \oplus w_l^T h_l), \forall k, 1 \le k \le K \tag{12}$$

$$F = \{f_l\}, \forall l, 1 \le l \le L \tag{13}$$

The top layer SCA model may use this failure matrix to compute dual failure disjoint backup paths Q in (1)-(8). This way, the dual failure protection may be cordinated using the bottom layer single failure protection schemes to compute H and W, then compute the IP layer working and backup paths in P and Q as long as they are disjoint based on the dual failure matrix F. To guarantee the connectivity constraint, the primary and secondary topology mapping matrics in H and W should also maintain the relationship in the following survivbale topology requirements in (10), (14)-(19):

$$\min_{W, s^b, G^b, F} \quad e^T s^b \tag{14}$$

$$\text{subject to: } W {B^b}^T = [\, B^T \mid 0 \,] \tag{15}$$

$$T^b + W \le 1 \tag{16}$$

$$G^b = W^T M^b H \tag{17}$$

$$s^b = \max G^b \tag{18}$$

$$C F^T < Ce \tag{19}$$

This is a survivable mapping model to guarantee IP/MPLS layer could remain connected under any dual link failures on the optical layers. It optimizes the total spare capacity on the optical layer in (14). The spare capacity is shared among backup paths in the secondary mapping W, after the primary mapping H is given. Equation (15) maintains the flow conservation constraints for W. The link disjoint requirement is enforced in (16) and (10). The spare capacity sharing is collected in (17) and summarized in (18), similar to the SCA model in (2)-(3). Equation (19) enforces each dual link failure k will not complete disconnect any cuts on the IP layer.

E. Consider Two-Connected Optical Layers

Many realistic networks might not be perfectly three-connected as asked by the protection synergy scheme for dual failure. On a two-connected optical layer, certain dual failures could partition the optical network and making packet links unable to be restored. These dual failures are also called the cut-pairs. A cut-pair contains two different links whose removal will partition the original graph. Tsin's algorithm may identify all cut-pairs in the linear-time complexity [15]. We used it in [16] to develop the partial disjoint backup paths in SBPP for dual failures on the single-layer networks.

In the protection synergy formulation above, the dual failures caused by the cut-pairs on two-connected optical layer should be removed in the failure matrix, i.e., replacing (11) with (20) below. This allows the optical layer to be two-connected instead three-connected while still be able to provide protection synergy for all possible dual failure scenarios.

$$f_{kl} = \begin{cases} 0, & \text{if } k \text{ or links } (i,j) \text{is a cut pair;} \\ h_{li}w_{lj} \oplus w_{li}h_{lj}, & \text{otherwise.} \end{cases} \quad (20)$$

III. Numerical Study and Analysis

Four networks are used in the numerical study to illustrate the proposed protection synergy approach. Their parameters are listed in TABLE II. The topologies are in Fig. 3 to Fig. 6. The last three networks have two-connected optical layers, and their cut-pairs are listed in TABLE II. These cut-pairs may be ignored from all possible dual failure scenarios to be protected by the protection synergy using (20).

TABLE II. Networks for Numerical Study

	Net1	Net2	Net3	Net 4
N	6	8	10	12
L	9	14	16	24
N^b	10	13	17	50
L^b	22	23	31	82
#cut-pairs	0	1	2	7
cut-pairs	NA	1-8, 1-9	1-12, 3-12;10-15,10-16	1-15,1-19; 6-41,12-43; 6-38, 37-38;11-49,11-50;15-16,16-17;36-42, 36-43; 39-40, 40-44

Two approaches are used to find the primary optical paths for all packet links, or alternatively the primary mapping matrix H. The first approach, *Shortest* H, simply finds a shortest optical path for each packet link. The second approach, *Survivable* H, will find H using the survivable topology mapping problem in (21)-(23), (10). This formulation was originally given in [7] and we have extended it for general failure scenarios in [9]. It requires the primary mapping matrix H to be designed so that the packet layer topology remains connected under any single fiber cuts.

$$\min_H \quad e^T He \quad (21)$$

$$\text{subject to: } HB^{b^T} = [\, B^T \mid 0 \,] \quad (22)$$

$$CU^b < Ce \quad (23)$$

Equation (21) minimizes the total hops of all optical paths in the primary topology mapping matrix H. The flow balance constraints in (22) ask all IP links to be carried by the corresponding optical paths. Survivable topology mapping constraints in (23) enforce that any single fiber cut do not partition the packet layer topology. It is similar to simulate each individual fiber cut while checking the packet layer to maintain at least one un-interrupted link.

At this moment, the secondary topology mapping in W is not considered yet. Due to the existence of backup optical paths in W, the survivable topology mapping requirements enforced in (23) are actually not necessary for H for the first failure. However, if dual link failures impact both working and backup optical paths for the same packet link and consequently disconnect this packet link is considered in the protection synergy formulation in (19).

The secondary topology mapping in W is computed using (14)–(19) where the objective is to minimize the shared total spare capacity on optical layer in (14). The numerical results are obtained using AMPL/CPLEX. The primary and secondary mappings (or working and backup optical paths), and related metrics are summarized in TABLE III-VI respectively.

These results first verify that the proposed protection synergy approach is capable to coordinate single layer protection schemes on both layers to protect all possible dual failure scenarios. The presence of cut-pairs on two-connected optical layers can also be successfully resolved using (20). This maintains very good usability on real networks.

Secondly, the total shared spare capacity among all secondary mappings in W has been significantly reduced comparing to the total capacity used by the primary mapping in H. This reduces the network overbuilt significantly, to a level below 100% and similar to those achieved from SBPP on single-layer single-failure cases. Since we uses the restoration against single failure on the packet layer which only requires a connectivity constraint in the survivable mapping at the moment, a comparison on spare capacity used is difficult here and we left this for future study.

Thirdly, the survivable H results computed using (21)-(23) on these networks seem to have little gain on the total spare capacity comparing to those uses the shortest H method, as shown in Fig. 2,. However, the average hops on both methods do differ significantly. The survivable H method seems to generate shorter backup paths comparing to the shortest H method.

It is reasonable to assume that the shortest H approach is enough to compute the primary mapping H, instead of using the more complicated survivable mapping formulation in (21)-(23). However, if the shorter backup optical paths are also preferred, it might be worth the effort to compute the survivable H.

At last, we use the survivable mapping formulation in (14)-(19) to find the secondary mapping W, because of the constraints in (19), the packet layer topology will remain connected under all dual failures defined in f_{kl} from (11) or (20). This satisfies the connectivity requirement on the packet layer. It allows the restoration scheme on the packet layer to respond to any dual link failure on the optical layer and provide 100% restorability for dual failure.

IV. Conclusion and Future Work

This paper proposes the protection synergy approach to protect any dual failure scenarios by coordinating single failure protection schemes on both layers. Numerical results show that maximum dual failure restorability can be achieved while minimizing the total spare capacity. This provides an additional advantage for integrated IP-over-optical networks.

The protection coordination is still working-in-progress. Several directions can be explored in the future. The first is to study SBPP on the packet layer for dual fiber cut as discussed in Section 0. The second is to analyze various protection and restoration combinations, such as SBPP, FRR, and restoration, on both layers in and study their influences to the protection coordination, as started in Section II.A. The third direction is to perform extensive numerical study to better understand the impact of protection coordination. We thank anonymous reviewers for their valuable comments and suggestions.

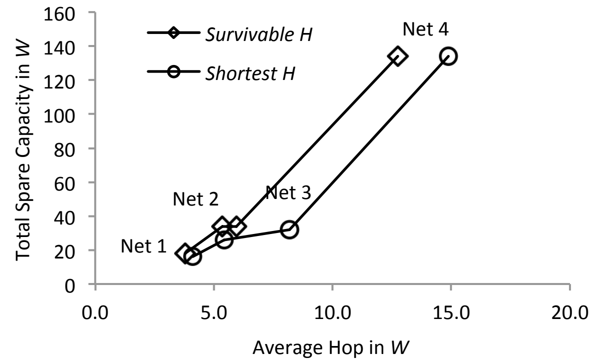

Fig. 2: Comparison on Total Spare Capacity and Average Hop in *W* between the *Shortest H* and the *Survivable H* methods on four networks

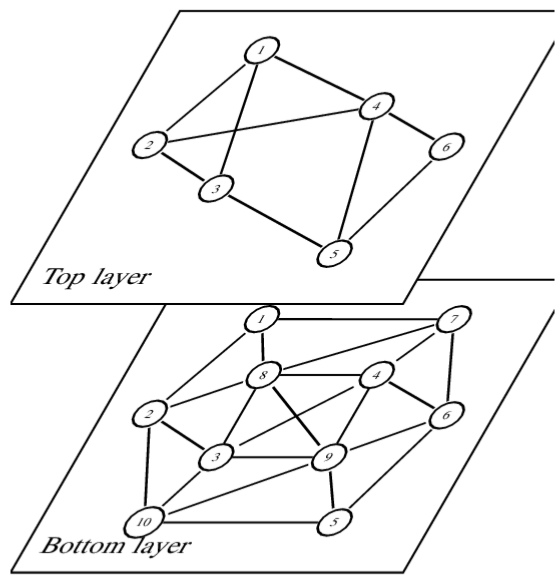

Fig. 3: Net1 ($N = 6, L = 9, N^b = 10, L^b = 22$, no cut pair)

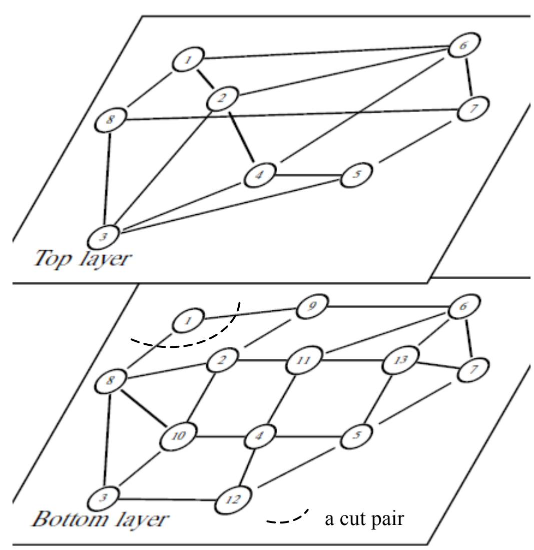

Fig. 4: Net2 ($N = 8, L = 14, N^b = 13, L^b = 23$, 1 cut pair)

REFERENCES

[1] J. P. Fernandez-Palacios, et. al., “IP and Optical Convergence: Use Cases and Technical Requirements,” white paper, Jan 2014, Online at http://www.tid.es/sites/526e527928a32d6a7400007f/assets/532c7ce328a32d4d710006bd/White_paper_IP_Optical_Convergence__1_.pdf.

[2] O. Gerstel, C. Filsfils, T. Telkamp, M. Gunkel, M. Horneffer, V. Lopez, and A. Mayoral, “Multi-Layer Capacity Planning for IP-Optical Networks,” IEEE Communications Magazine, Jan. 2014.

[3] R.G. Prinz, A. Autenrieth, and D.A. Schupke, “Dual failure protection in multilayer networks based on overlay or augmented model,” in International Workshop on Design of Reliable Communication Networks (DRCN), Island of Ischia, Naples, Italy, Oct. 16–19 2005.

[4] V. Y. Liu and D. Tipper, “Spare capacity allocation using shared backup path protection for dual link failures,” in Computer Communications, Special Issue on Reliable Network Services, vol. 36, no. 6, March 15, 2013, pp. 666-677. http://dx.doi.org/10.1016/j.comcom.2012.09.007

[5] M. Clouqueur and W. D. Grover, “Availability analysis of span-restorable mesh networks,” IEEE Journal on Selected Areas of Communications, vol. 20, no. 4, pp. 810–821, May 2002.

[6] J. Doucette, M. Clouqueur, and W. D. Grover, “On the availability and capacity requirements of shared backup path-protected mesh networks,” Optical Networks Magazine, vol. 4, no. 6, pp. 29–44, Nov./Dec. 2003.

[7] E. Modiano and A. Narula-Tam, "Survivable lightpath routing: a new approach to the design of WDM-based networks," IEEE Journal of Selected Areas in Communication, May 2002.

[8] M. Kurant and P. Thiran, “Survivable Routing of Mesh Topologies in IP-over-WDM Networks by Recursive Graph Contraction,” IEEE Journal on Selected Areas in Communications, vol. 25, no. 5, June 2007.

[9] Y. Liu, D. Tipper, and K. Vajanapoom, “Spare capacity allocation in two-layer networks,” IEEE Journal on Selected Areas of Communications, vol. 25, no. 5, pp. 974–986, Jun. 2007.

[10] Z. Sui and V.Y. Liu, “Dual failure resiliency on single failure protected packet optical integrated networks, ” in 11th Intl. Conf. on Design of Reliable Communications Network, Kansas City, MO, USA, March 25-27, 2015.

[11] Y. Liu, D. Tipper, and P. Siripongwutikorn, “Approximating optimal spare capacity allocation by successive survivable routing,” IEEE/ACM Trans. on Networking, vol. 13, no. 1, pp. 198–211, Feb. 2005.

[12] Yu Liu, Spare capacity allocation method, analysis and algorithm, Ph.D. dissertation, Telecommunications Program, School of Information Sciences, University of Pittsburgh, 2001.

[13] K. Thulasiraman, M. S. Javed, and G. Xue, “Circuits/Cutsets duality and a unified algorithmic framework for survivable logical topology design in IP-over-WDM optical networks,” in IEEE INFOCOM, 2009.

[14] Z. Zhou, T. Lin, K. Thulasiraman, G. Xue, and S. Sahni, “Novel Survivable Logical Topology Routing in IP-over-WDM Networks by Logical Protecting Spanning Tree Set,” in the proceedings of 4th Intl. Workshop on Reliable Networks Design and Modeling (RNDM), co-located with ICUMT 2012 Conference. Oct. 3-5, 2012, St. Petersburgh, Russia.

[15] T. H. Tsin, “Yet another optimal algorithm for 3-edge-connectivity,” Journal of Discrete Algorithms, 7:130–146, 2009.

[16] V. Y. Liu, D. Tipper, “Spare Capacity Allocation Using Partially Disjoint Paths for Dual Link Failure Protection.” In 9th International Workshop on the Design of Reliable Communication Networks (DRCN), Budapest, Hungary, pp. 171-178, March 4-7. 2013.

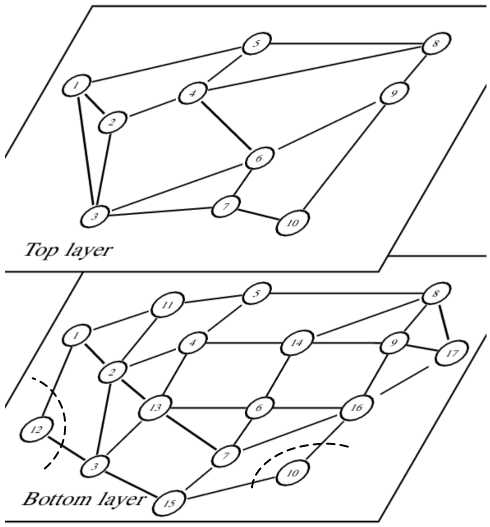

Fig. 5: Net3 ($N = 10, L = 16, N^b = 17, L^b = 31$, 2 cut pairs)

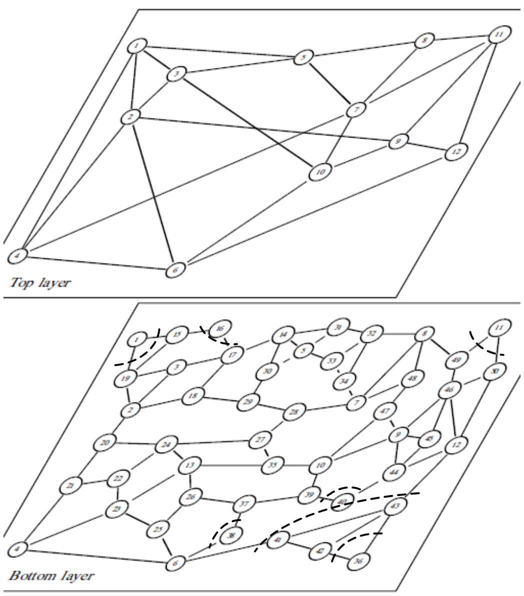

Fig. 6: Net4 ($N = 12, L = 24, N^b = 50, L^b = 82$, 7 cut pairs)

TABLE III. PRIMARY AND SECONDARY OPTICAL PATHS AND RESULTS ON NET1

Link	1: Shortest Paths for H		2: Survivable Topology Design for H	
	H	W	H	W
	$\sum H$=28	$\sum s^b$=16	$\sum H$=28	$\sum s^b$=18
1-2	1-2	1-7-6-5-10-3-2	1-2	1-7-4-9-5-10-2
1-3	1-8-3	1-2-3	1-8-3	1-7-4-3
1-4	1-7-4	1-2-3-4	1-7-4	1-2-10-5-9-4
2-3	2-3	2-1-7-6-5-10-3	2-3	2-10-5-9-4-3
2-4	2-8-4	2-3-4	2-3-4	2-1-7-4
3-5	3-9-5	3-10-5	3-10-5	3-4-9-5
4-5	4-9-5	4-3-2-1-7-6-5	4-6-5	4-9-5
4-6	4-6	4-3-10-5-6	4-6	4-7-6
5-6	5-6	5-10-3-2-1-7-6	5-6	5-10-2-1-7-6
avg. hop	1.6	4.1	1.6	3.8
time		0.24 sec	0.04sec	0.14sec

TABLE IV. PRIMARY AND SECONDARY OPTICAL PATHS AND RESULTS ON NET2

Link	1: Shortest Paths for H		2: Survivable Topology Design for H	
	H	W	H	W
	$\sum H$=50	$\sum s^b$=26	$\sum H$=50	$\sum s^b$=34
1-2	1-9-2	1-8-2	1-8-2	1-9-2
1-6	1-9-6	1-8-3-10-4-5-7-6	1-9-6	1-8-2-10-3-12-4-5-7-13-6
1-8	1-8	1-9-6-7-5-4-10-3-8	1-8	1-9-6-11-2-8
2-3	2-10-3	2-8-3	2-8-3	2-11-6-7-5-4-12-3
2-4	2-10-4	2-11-6-7-5-4	2-11-4	2-10-3-12-4
2-6	2-9-6	2-11-6	2-9-6	2-11-6
3-4	3-12-4	3-10-4	3-10-4	3-12-4
3-5	3-12-5	3-8-1-9-6-7-5	3-12-5	3-10-2-9-6-7-5
3-8	3-8	3-10-4-5-7-6-9-1-8	3-8	3-10-2-8
4-5	4-5	4-10-3-8-1-9-6-7-5	4-5	4-12-3-10-2-9-6-13-7-5
4-6	4-11-6	4-10-3-8-1-9-6	4-11-6	4-5-7-6
5-7	5-7	5-4-10-3-8-1-9-6-7	5-7	5-4-12-3-10-2-9-6-13-7
6-7	6-7	6-9-1-8-3-10-4-5-7	6-7	6-11-2-10-3-12-4-5-7
7-8	7-13-11-2-8	7-6-9-1-8	7-6-11-2-8	7-13-6-9-1-8
avg. hop	1.8	5.4	1.8	5.4
Time		0.08 sec	0.14sec	1.3 sec

TABLE V. PRIMARY AND SECONDARY OPTICAL PATHS AND RESULTS ON NET3

Link	1: Shortest Paths for H		2: Survivable Topology Design for H	
	H	W	H	W
	$\sum H$=50	$\sum s^b$=32	$\sum H$=50	$\sum s^b$=34
1-2	1-2	1-12-3-15-7-6-16-9-8-14-4-2	1-2	1-11-2
1-3	1-12-3	1-2-4-14-8-9-16-6-7-15-3	1-2-3	1-12-3
1-5	1-11-5	1-12-3-15-7-6-16-9-8-14-4-5	1-11-5	1-12-3-15-10-16-9-8-5
2-3	2-3	2-4-5-8-9-16-6-7-15-3	2-3	2-11-5-8-9-16-10-15-3
2-4	2-4	2-1-12-3-15-7-6-16-9-8-14-4	2-4	2-11-1-12-3-15-10-16-9-8-14-4
3-6	3-13-6	3-15-7-6	3-13-6	3-15-10-16-6
3-7	3-15-7	3-12-1-2-4-14-8-9-16-6-7	3-15-7	3-12-1-11-5-8-9-16-7
4-5	4-5	4-2-1-12-3-15-7-6-16-9-8-5	4-5	4-2-11-1-12-3-15-10-16-9-8-5
4-6	4-14-6	4-2-1-12-3-15-7-6	4-13-6	4-14-8-9-16-7-6
4-8	4-5-8	4-14-8	4-5-8	4-14-8
5-8	5-8	5-4-2-1-12-3-15-7-6-16-9-8	5-8	5-11-1-12-3-15-10-16-9-8
6-7	6-7	6-16-9-8-14-4-2-1-12-3-15-7	6-7	6-16-7
6-9	6-14-9	6-16-9	6-14-9	6-16-9
7-10	7-16-10	7-15-10	7-15-10	7-6-16-10
8-9	8-9	8-14-4-2-1-12-3-15-7-6-16-9	8-9	8-5-11-1-12-3-15-10-16-9
9-10	9-16-10	9-8-14-4-2-1-12-3-15-10	9-16-10	9-8-5-11-1-12-3-15-10
avg. hop	1.6	8.2	1.6	5.9
time		0.28 sec	0.61sec	0.55 sec

TABLE VI. PRIMARY AND SECONDARY OPTICAL PATHS AND RESULTS FOR ON NET4

Link	1. Shortest Paths for H		2. Survivable Topology Design for H	
	H	W	H	W
	$\sum H$=148	$\sum s^b$=134	$\sum H$=148	$\sum s^b$=134
1-2	1-19-2	1-15-16-17-18-2	1-19-2	1-15-16-17-14-5-31-32-8-49-11-50-46-9-47-48-7-28-29-18-2
1-3	1-19-3	1-15-16-17-3	1-19-3	1-15-19-2-18-29-28-27-24-22-23-4-6-41-43-12-50-11-49-8-32-31-14-17-3
1-4	1-19-2-20-21-4	1-15-19-3-17-14-5-33-34-7-48-47-9-44-12-43-41-6-4	1-19-2-20-21-4	1-15-19-3-17-18-29-28-27-35-13-23-4
1-5	1-19-3-17-14-5	1-15-19-2-18-29-28-7-48-47-10-9-46-50-11-49-8-32-31-5	1-15-16-17-14-5	1-19-2-18-29-28-27-24-22-23-4-6-41-43-12-50-11-49-8-32-31-5
2-3	2-3	2-19-3	2-3	2-18-17-16-15-19-3
2-4	2-20-21-4	2-18-29-28-27-35-13-23-4	2-20-21-4	2-18-29-28-27-24-22-23-4
2-6	2-20-21-4-6	2-18-29-28-27-24-13-23-25-6	2-20-21-4-6	2-19-15-16-17-14-5-31-32-8-49-11-50-12-43-41-6
2-9	2-20-24-27-35-10-9	2-9-15-16-17-14-31-32-8-49-11-50-46-9	2-20-24-27-35-10-9	2-18-29-28-7-48-47-9
3-5	3-17-14-5	3-19-15-16-17-18-29-28-27-35-13-23-4-6-41-43-12-44-9-47-48-7-34-33-5	3-17-14-5	3-19-15-16-17-18-29-28-7-8-32-31-5
3-10	3-2-20-24-27-35-10	3-17-14-31-32-8-48-47-10	3-2-20-24-13-35-10	3-17-14-31-32-8-49-11-50-46-9-10
4-6	4-6	4-23-13-35-27-28-7-34-33-5-14-31-32-8-49-11-50-12-43-41-6	4-6	4-23-22-24-27-28-29-18-17-14-31-32-8-49-11-50-12-43-41-6
4-7	4-23-13-35-27-28-7	4-6-41-43-12-44-9-47-48-7	4-21-20-24-27-28-7	4-6-41-43-12-50-11-49-8-7
5-7	5-33-34-7	5-14-17-3-19-15-16-17-18-29-28-7	5-33-34-7	5-14-17-18-29-28-7
5-8	5-33-32-8	5-31-14-17-16-15-19-2-18-29-28-27-35-13-23-4-6-41-43-12-50-11-49-8	5-31-32-8	5-14-17-18-29-28-27-24-22-23-4-6-41-43-12-50-11-49-8
6-10	6-38-37-39-10	6-41-43-12-50-46-9-10	6-38-37-39-10	6-41-43-12-50-46-9-10
6-12	6-41-43-12	6-4-23-13-35-27-28-29-18-2-19-15-16-17-14-31-32-8-49-11-50-12	6-41-43-12	6-4-23-13-35-27-28-7-48-47-9-46-50-12
7-8	7-8	7-48-47-10-9-46-50-11-49-8	7-8	7-28-27-35-13-23-4-6-41-43-12-50-11-49-8
7-10	7-48-47-10	7-28-29-18-17-14-31-32-8-49-11-50-12-44-9-10	7-48-47-10	7-28-27-24-22-23-4-6-41-43-12-50-46-9-10
7-11	7-8-49-11	13-23-25-6-41-43-12-50-11	7-8-49-11	7-48-47-9-46-50-11
8-11	8-49-11	8-32-31-5-33-34-7-48-47-9-46-50-11	8-49-11	8-32-31-14-17-18-29-28-27-24-22-23-4-6-41-43-12-50-11
9-10	9-10	9-47-10	9-10	9-46-50-12-43-41-6-4-23-22-24-27-35-10
9-11	9-46-49-11	9-44-12-50-11	9-46-49-11	9-10-35-13-23-4-6-41-43-12-50-11
9-12	9-46-12	9-10-47-48-7-34-33-5-31-32-8-49-11-50-12	9-44-12	9-46-50-12
11-12	11-50-12	11-49-8-32-31-14-17-3-19-2-18-29-28-27-35-13-23-4-6-41-43-12	11-50-12	11-49-8-32-31-14-17-18-29-28-27-24-22-23-4-6-41-43-12
avg. hop	3.1	14.9	3.1	12.8
time		42 min	46sec	22 min