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Algorithmic Design for Multi-Layer Survivable Networks and Failure Recovery

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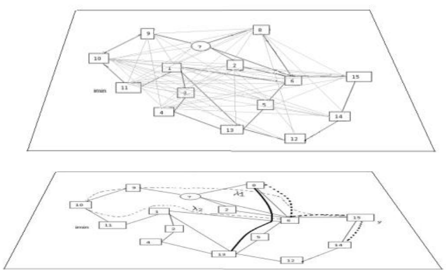
Abstract*—In this paper we investigate and discuss different issues that arise in multilayer networks with respect to their survivability. We argue necessity of dynamic optimal routing and recovery mechanism to support dynamically changing technologies in multilayer architecture. We argue that there are situations where algorithms used in single layer network, such as BGP,SS7 and OSPF-TE where shortest path is not calculated. To solve this problem both multilayer representation as well as new path finding algorithms need to be investigated. Here the challenge is to design generic minimum alternative logical path finding algorithm that is technology –independent and not requires any modifications as new technologies emerge. We also show that our algorithm selects each logical edge carrying lower traffic to find a promising edge and also assigns the wavelength and forms survivable logical topology.

Key words— **Communication Network, Survivable network, Multilayer Network, WDM Network, Light path, Wavelength, NDL**

I. INTRODUCTION

Communication networks consist of a stack of sub networks with different technologies, so-called layers. Every link in an upper layer is realized by one or more paths in the next lower layer. For example, an IP link between two Internet routers may be realized by one or more light paths in an underlying optical fiber network, as illustrated in Figure.1



IPLayer

Optical

Fiber Layer

Fig .1: A multi-layer network. The upper layer might correspond to an Internet backbone IP network and the lower layer to an optical fiber network. The IP connection between two Internet routers in Node8 and Node14 is realized by the two light paths in the underlying fiber network between the Same nodes. All traffic sent on this seemingly direct link actually travels via one of the two paths.

Network design

Modern communication networks accommodate various kinds of traffic. This includes, but is not limited to, IP traffic from the Internet, traffic from dedicated virtual private networks of large companies, video traffic, and voice traffic from fixed-line or mobile telephone calls. To route all this data through the network, the network nodes have to be equipped with routing and switching hardware to receive traffic on an incoming link and send it out on some outgoing link. Furthermore, the links between these nodes must provide sufficient capacity (reserved bandwidth) to accommodate all requested connections. Usually, this capacity can only be installed in discrete steps. When building such a network, or when adapting an existing network to changing demands, the network operator faces a network design problem. Network design problems occur in many different flavors depending on the specific technologies and side constraints. Stated in a general form, such a problem consists of choosing a set of nodes with links between them(a so-called network topology), installing capacities on the links and hardware at the nodes, and routing the traffic demands of all customers within these capacities. During this design process, a variety of hardware compatibility constraints and routing constraints has to be taken into account. In order to protect the traffic against hardware failures or cable cuts, spare capacity may have to be installed in the network in such a way that affected traffic can be rerouted around the failing node or link. This is illustrated in Figure 2. Many optimization goals are possible, such as minimizing total installation cost or accommodating as much traffic as possible in a given network configuration.

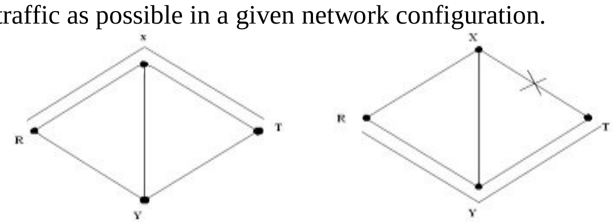


Fig .2: Survivability by 1:1 protection: normally, the flow from s to t is routed on the paths–u–t. If this path fails, its flow is switched to the disjoint backup path s–v–t, which must have been equipped MATH with sufficient capacity during the network design phase. Many other possible rerouting schemes have been proposed in the literature.

Mathematical models and algorithms to solve such network design problems have been extensively studied during the last twenty years. Much progress has been made in this area, and many large network design problems can nowadays be solved to a degree which is sufficient for practical applications. Computing an *optimal* network configuration and proving its optimality, on the other hand, can still be a challenge.

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II. INTRODUCTION TO MULTI-LAYER NETWORK

Unfortunately, real telecommunication networks are more complicated than just described. They consist of a complex hierarchy of *layers*. For instance, an IP link in a nationwide backbone network is usually not realized as a direct connection in the form of an Ethernet cable or a radio link. Instead, it is realized by one or more paths in an underlying transport layer, such as lightpath connections in an optical fiber network. When focusing on two adjacent network layers from the hierarchy, a link realized by a path in some underlying transport layer is called a *logical link* (or *virtual link*), while the links of the realizing path in the transport layer are called *physical links*.

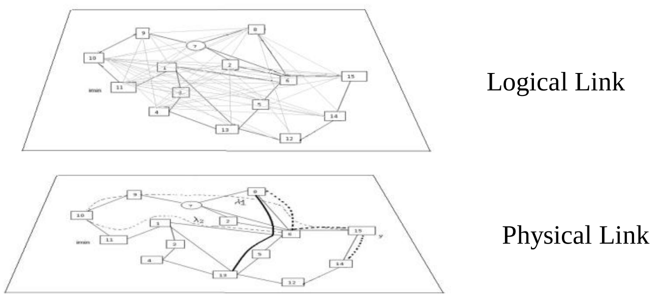

Fig 3: A Multi-layer backbone network. The dashed logical link Node8–Node14 is realized by a physical path between these nodes via Node6. The solid logical link Node8–Node12 is realized by a path from Node8 via Node6 and Node5 to Node12. A communication demand from Node14 to Node12 may be routed on a path in the logical layer fromNode14 via Node15 to Node6. It cannot leave the physical paths at intermediate nodes.

Such a multi-layer network is illustrated in Figure 3. It shows an upper logical layer based on an underlying physical layer. Both layers are based on the same set of nodes, corresponding to important network nodes in a backbone network. In an optical networking context, the lower physical layer represents a fiber network where each link in the upper logical layer is realized by a light path connection between the corresponding end-nodes in the fiber layer. In Figure 3, the solid logical link between Node8 and Node13 is realized by a path between these cities via Node6 and Node5. The dashed logical link between Node8 and Node14 is implemented by the path Node8–Node6–Node15–Node14. A demand fromNode14 to Node13 may be routed via Node6 on a path consisting of these two logical links. It is *not* possible for the demand to quit the physical paths and to take the shortcut Node14–Node12–Node13, for instance; all data entering a logical link at its source node must travel the whole link until its target node. Usually, the requested bandwidth of a communication demand is much lower than the capacity provided by a logical link, such that a logical link can accommodate the routing paths of many demands simultaneously. The figure also illustrates the potential impact of physical failures on the logical layer. Both logical links traverse the Node6. Hence, an equipment failure at Node6 causes both logical links to break down simultaneously, as well as all connections between end users which are routed through any of these links, such as the connection Node14–Node13. When looking at the logical layer alone, these links seem to be disjoint and independent of node Node6. Similar considerations hold if a cable cut occurs between Node8 and Node6. This example shows that routing decisions in the upper layer must take the realization of logical links in the underlying physical layer into account to achieve survivability against equipment failures. If you are using Word, use either the Microsoft Equation Editor or the Math Type add-on (http://www.mathtype.com) for equations in your paper (Insert | Object | Create New | Microsoft Equation or Math Type Equation). “Float over text” should not be selected.

III. OPTIMAL DYNAMIC ROUTING AND WAVELENGTH ASSIGNMENT

A. The Problem

For path finding, it is necessary to have the details of of different encodings in order to avoid incompatibilities in a path. Finding shortest light path is highly nontrivial, and a recent study shows that shortest paths can even contain loops. This counter-intuitive behaviour is caused by incompatibilities between different networks that force the shortest path to include network domains that can convert between different encodings. Exchanging information about encodings and topologies between network domains is essential for path finding

B. Multi-Layer Network Descriptor

In this paper we assume that network description language (NDL) is a schema that allows domains to describe and exchange information about their networks. Using this NDL, routing algorithm obtains the global network state by exchanging the link state advertisements. Ideally, every time the state of a link is changed, e.g. a wavelength is used or released by a connection; the changing of the link state must be made known to all routers in the networks. However, due to the overhead concerns, the link state updates usually cannot keep up with the actual link state changes. Hence, the global state maintained at each node may not accurately reflect the current network situation. In addition to the overhead consideration, other factors, such as the large propagation delay and topology aggregation schemes, which summarize network state information in a concise representation, can contribute to the imprecision of the global network state information. Thus, a practical dynamic routing and wavelength assignment algorithm must be able to deal with imprecise global state information and perform effective Optimal and dynamic routing and wavelength assignment.

IV. METHODOLOGY

The algorithm proposed here describes the procedure to find optimal solution for multilayer network to find an alternative path for multilayer failure. The algorithm includes problem reductions, cutting planes and decomposition procedure to deal with larger networks.

A. Multi-Layer network models

This section introduces all necessary problem parameters for The Network The physical network is represented by an

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undirected graph G_p = (V,E). The logical network is modeled by an undirected graph G_L = (V,L) with the same set of nodes and a fixed set L of admissible logical links, where each $l \in L$ is defined by an undirected in the physical network. Consequently, there may be many parallel logical links corresponding to different physical s between any two nodes. Let $\delta_L(i) \subseteq$ L be the subset of all logical links incident to node $i \in V$, i. e., starting or ending at i. For ease of notation, we define $L_{ij} := \delta_L(i) \cap \delta_L$ as the subset of all logical links connecting nodes i and j, with $L_{ii} := \emptyset$ for all $i \in V$ (that is, we disallow loops in the logical network). $L_e \subseteq$ L refers to the sets of logical links containing physical link $e \in E$. Likewise, $L_i \subseteq$ L denotes the set of logical links containing i as an inner node (not as an end-node). In a real network, various devices may be installed at each location in different network layers. In our model, the nodes represent whole locations (e. g., cities) rather than individual devices.

Capacities Installation: Each logical link $l \in L$ has a set M_l of installable capacity modules (different bit-rates, e. g., 2.5, 10, or 40 Gbit/s) that can be installed in arbitrary Combination. Each module $m \in M_l$ has a capacity of $C_l^m \in Z_+$ and a cost of $k_l^m \in R_+$. Similarly, every node $i \in V$ has a set M_i of installable node modules, at most one of which may be chosen. Every node module $m \in M_i$ has a switching capacity of $C_i^m \in Z+$ (e. g., in Gbit/s) and a cost of $k_i^m \in R+$. On a physical link $e \in E$, capacities can be installed at a cost of $k_e \in R+$ per unit (corresponding to fibers, for example). Each physical capacity unit supports up to $B_e \in Z+$ logical capacity modules (e. g., lights).

Construction of protected Routes: Connection requests between the network nodes are modeled by a set $R = R_p \cup R_u$ of undirected point-to-point demands, where R_p comprises the 1+1 protected demands and R_u the unprotected ones. Protected demands are expected to survive multiple physical node and link failures. For $i, j \in V$ i, let $R_{ij} \subseteq$ R be the subset of demands defined between nodes i and j. We assume $R_{ii} = \emptyset$ for all $i \in V$, that is, we exclude demands from a node to itself. For each demand $r \in Rij$, a demand value of d_r has to be routed between i and j, i.e., a bandwidth of dr has to be reserved between these nodes (in arbitrary direction). For 1+1-protected demands, protection is modeled by doubling the demand value and requiring that at most the origin i $\in K_p$nal demand value is routed through any single physical link or node. In this way, it is guaranteed that at least the original demand survives any single or multiple physical link or node failure. For protected demands, the notation d_r therefore refers to twice the original demand value that would have to be routed if the demand was unprotected. From now on, these demands are assumed to be directed in an arbitrary way. For any pair of nodes $i, j \in V$, let R_{ij} be the set of all demands directed from i to j, where $R_{ii} = \emptyset$ for all $i \in V$. As the direction of the demands is arbitrary, we may assume without loss of generality that for all nodes $, j \in V$, either R_{ij} or R_{ji}Rji is empty.

Construction Procedure:

For $K = K_p \cup K_u$ (protected and unprotected Path) Every protected path k consists of a single 1+1 protected point-to-point demand. In contrast, unprotected path $k \in K_u$ are derived by aggregating all unprotected point-to-point demands that share a common source node. The source node of a path is defined in a natural way by the source node of its demands. A protected path has exactly one target node $t_k \in V$, where as an unprotected path may have several ones.

V. MATHEMATICAL MODEL

Basic Model

This model is called Unprotected-Base-Model. Variables The model comprises four classes of variables representing the traffic flow and different capacity types.

1. For each logical link ℓ ∈ L and each module m ∈ M_l, the logical link capacity variable $y_l^m \in Z_+$ represents the number of modules of type m installed on ℓ.
2. For any physical link e ∈ E, the integer physical link Capacity variable $z_e \in Z_+$ denotes the number of capacity units installed on physical link e.
3. For each node i ∈ V and each node module m ∈ M_i, the binary variable $x_i^m \in \{0, 1\}$ denotes whether module m is installed at node i or not.
4. Eventually, the flow variables $f_{l,ij}^k, f_{l,ji}^k \in R_+$represent the flow for commodity k ∈ K on logical link $l \in L_{ij}$ directed from i to j and from j to i, respectively.

Resulting Model

$$min \sum_{i\in V} \sum_{m\in Mi} k_i^m x_i^m + \sum_{l\in L} \sum_{m\in Mi} k_l^m y_l^m + \sum_{e\in E} k_e z_e$$

Protection against physical node or link failures:

Some of Basic terminologies:

$$Node\ Pair \rightarrow \sum_{l\in L_{ij}} \sum_{m\in M_l} C_l^m y_l^m - \sum_{k\in K} (f_{ij}^k + f_{ji}^k) \geq 0 \quad \forall i,j \in V, i \neq j$$

$$Capacity\ Constraits \rightarrow \sum_{m\in M_l} C_l^m y_l^m - \sum (f_{l,ij}^k + f_{l,ji}^k) \geq 0 \quad \forall i,j \in V, l \in L_{ij}$$

$$Additional\ Demand \rightarrow \sum_{j\in V} \sum_{l\in Lij} (f_{l,ij}^k - f_{l,ji}^k) = d_i^k \quad \forall_i \in V, \quad \forall_k \in K^p$$

$$Survivability\ Constrain \rightarrow \frac{1}{2} \sum_{l\in\delta(v)} (f_{l,ij}^k + f_{l,ji}^k) + \sum_{l\in L^p} (f_{l,ij}^k - f_{l,ji}^k) \leq \frac{d^k}{2} \quad \forall_k \in K^p,$$

$$Survivability\ Constraints \rightarrow \sum_{l\in L^p} (f_{l,ij}^k - f_{l,ji}^k) \leq \frac{d^k}{2} \quad \forall_k \in K^p, \forall_e \in E$$

For commodities $k \in K_p$, which are protected against physical node or link failures, the realization of a logical link in the physical layer has to be taken into account in the model. Consequently, the logical link flow variables cannot be aggregated as in the previous section. In addition to the node-pair flow variablesf_{ij}^k for unprotected commodities, we thus introduce logical link flow variables $f_{l,ij}^k$ for protected commodities. We exclude those logical link flow variables $f_{l,ij}^k, f_{l,ji}^k$ where the logical link ℓ contains an end-node of the protected path k as an inner node. Moreover, we do not generate flow variables into the source or out of the target of a protected (point-to-point) path to avoid unwanted

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cycle flows. That is, the set of admissible flow variables for protected commodities can be described as below

$\{ \ f^k_{l,ij} \mid k \in K^p, i,j \in V, i \neq j, l \in L_{ij} \setminus \{L^{s^k} \cup L^{t^k}\}, i \neq t^k, j \neq s^k \ \}$

The node-pair and logical link capacity constraints are adapted to the new variables, and additional demand and survivability constraints ensure that enough flow is routed both in the normal network state and in any single node or physical link failure state. The model Protected with protected and unprotected commodities reads as follows:

Protected Model:

$$\min \sum_{i \in V} \sum_{m \in M_i} k^m_i x^m_i + \sum_{l \in L} \sum_{m \in M_l} k^m_l y^m_l + \sum_{e \in E} k_e z_e \quad [1]$$

$$\sum_{j \in V} \sum_{l \in L_{ij}} (f^k_{ij} - f^k_{ij}) = d^k_i \qquad \forall i \in V, \forall_k \in K^u \quad [2]$$

$$\sum_{j \in V} \sum_{l \in L_{ij}} (f^k_{l,ij} - f^k_{l,ji}) = d^k_i \qquad \forall_i \in V, \quad \forall_k \in K^p [3]$$

$$\frac{1}{2} \sum_{l \in \delta(v)} (f^k_{l,ij} + f^k_{l,ji}) + \sum_{l \in L^v} (f^k_{l,ij} - f^k_{l,ji}) \leq \frac{d^k}{2} \qquad \forall_k \in K^p, \forall_v \in V [4]$$

$$\sum_{l \in L^e} (f^k_{l,ij} - f^k_{l,ji}) \leq \frac{d^k}{2} \qquad \forall_k \in K^p, \forall_e \in E [5]$$

$$\sum_{m \in M_l} C^m_l y^m_l - \sum_{k \in K^p} (f^k_{l,ij} + f^k_{l,ji}) \geq 0 \qquad \forall i \in j, \forall_l [6]$$

$$\sum_{l \in L_{ij}} \left(\sum_{m \in M_l} C^m_l y^m_l - \sum_{k \in K^p} (f^k_{l,ij} + f^k_{l,ji}) \right) - \sum_{k \in K^p} (f^k_{ij} + f^k_{ji}) \geq 0$$

$$\forall i \in j, i \neq j \quad [7]$$

$$\sum_{m \in M_i} x^m_i \leq 1 \qquad \forall_i \in V \quad [8]$$

$$\sum_{l \in L_{ij}} C^m_i x^m_i - \sum_{l \in \delta_{L(i)}} \sum_{m \in M_l} C^m_l y^m_l \geq C_i \qquad \forall_i \in V \quad [9]$$

$$B_e z_e - \sum_{l \in L^e} \sum_{m \in M_e} y^m_l \geq 0 \qquad \forall_i \in E [10]$$

$$f^k_{l,ij}, f^k_{l,ji}, f^k_{ji}, f^k_{ji} \in R_+, y^m_l, z_e \in Z_+, x^m_i \in \{0,1\}$$

To model survivability, we use the diversification concept. The node diversification constraints [4] ensure that at most $\frac{d_k}{2}$ (i. e., the original demand value) is routed through any physical node, i. e., at least a flow of $\frac{d_k}{2}$ survives any single physical node failure. The first sum contains all logical links starting or ending in node v, whereas the second sum contains those logical links having v as an inner node. Notice that if node v is an end-node of path k, the second sum in the corresponding node diversification constraint [4] is empty. As we have also forbidden flow into the source node or out of the target node of k, this diversification constraint is dominated by the corresponding demand constraint [3] and can be omitted. The edge diversification constraints [5] ensure that the routing also survives single physical link failures. The capacity constraints from the model without protection are replaced by two new classes of inequalities. Constraints [6] state that the capacity of every single logical link should be sufficient to accommodate the protected flow on that link. Based on these inequalities, Constraints [7] ensure that between any two nodes i, j ∈ V , the total remaining capacity suffices to accommodate the unprotected flow. As in the previous model, the unprotected flow can be arbitrarily distributed within this free capacity in a post processing step-In the special case where all commodities are protected, i.e., K = Kp, Constraints are only aggregations of Constraints [6] and can be omitted.

VI. MODELING ALTERNATIVE PROTECTION

The multi-layer network may have several options to reconfigure parts of the routing in case of an equipment failure. These options are applicable or desirable depends on the technological context, long-term contracts, and other criteria. As we are dealing with transport networks, we assume that survivability against single physical link or node failures is ensured by 1+1 protection. This survivability mechanism, which is commonly used in transport networks, also provides survivability against single failures of ports or line cards. With 1+1-protection, a demand is routed on two physically node- and link-disjoint paths simultaneously, and the target node chooses the better of the two arriving signals. If any single node or link fails, at least one of these paths survives (unless one of the end-nodes fails).The assignment of backup paths for a given working path is fixed and does not depend on the failure state. One important consequence is that backup capacity cannot be shared between different demands depending on the failure state, but has to be reserved and preconfigured for each particular demand. Although this approach may require much backup capacity which is normally unused, it is attractive for network operators because nothing has to be reconfigured in case of a single node or link failure, such that all connections can be continued without disruption.

A. Wavelength assignment

In an IP over WDM, SDH or ATM setting, the logical links correspond to light paths in the fiber network, and wavelengths must be assigned to the light paths such that any two light paths sharing a common fiber have different wavelengths. In our model assignment of wavelength is technology-specific, and second, finding a conflict-free wavelength assignment is an extremely hard problem on its own. Our models limit the number of logical links that may traverse a given physical link. The approach for choosing between different wavelengths is to simply select one of the wavelengths at random. The wavelength selection is done in a distributed manner, with only limited or outdated information, then random wavelength assignment may outperform than other assignment approaches. The reason for this behavior is that, in other approaches, if multiple connections are attempting to set up a light path simultaneously, then it may be more likely that they will choose the same wavelength, leading to one or more connections being blocked.

Algorithm 1 Finding Optimal Routing

1. Input: commodities K, logical link cost κ_l, logical link capacities c_l.
2. Output: a routing for all paths satisfying the demand and diversification constraints, and capacity constraints with respect to c_l.
3. for all k ∈ K_u do

4. Hide all logical links $l \in L$ with $c_l < d^k/2$ from the graph.
5. Compute a shortest-path routing in the logical layer with respect to the $\kappa\ell$.
6. end for
7. for all $k \in K_p$ do
8. Hide all logical links $l \in L$ with $c_l < d^k/2$ from the graph.
9. Find a shortest logical path with respect to the given logical link cost.
10. Hide all logical links from the graph failing together with any link from the first path.
11. Find another shortest path in the remaining logical network.
12. If this approach fails,
13. end for

This iterative approach succeeds in finding two failure-disjoint paths. If the algorithm fails for some protected path $k \in K_p$, we use the more sophisticated but Also computationally more expensive algorithm Cover Physical Cycles, it is achieved in Algorithm 2

Algorithm 2. It computes two disjoint paths from s_k to t_k in the physical layer and covers them with cheap logical links.

Algorithm 2 Cover Physical Cycles

1. Input: a path $k \in K_p$, logical link cost κ_l, logical link capacities c_l.
2. Output: a routing for path k satisfying the routing constraints.
3. Find a shortest cycle through s_k and t_k in the physical graph with respect to some physical link cost. This yields two physical paths p1, p2 from s^k to t^k.
4. Cover p1, p2 with few logical links using an auxiliary graph H
5. for all $p \in \{p1, p2\}$ do
6. Define a node in H for every node of p.
7. for all $l \in L$ with $c_l \geq d_k/2$ do
8. If l is part of p, define an undirected edge in H with cost κ_l.
9. end for
10. Search for a shortest s_k-t_k path in H.
11. end for

After execution of algorithm1 & algorithm2 the algorithm3 is called to assign wavelength

Algorithm 3 Wavelength assignment using Random selection

1.For all $n \in V$,
n_i
$\in V' \, for \, i =$
$1,2, \ldots, k. In \; addition, two \; nodes \; src' and \; dst' are \; added \; to \; the \; graph$

$2. For \; an \; edge \, (u, v) \in E, (u_i$
$, v_i) \in$
$E' \; if \; and \; only \; if \; the \; ith \; wavelength \; on \; link \; (u,v) is \; available. in \; addition, links \; (src', src) \in$
$for \; i = 1,2, \ldots, k \; and \; (dst$
$, src_i) \; for \; i = 1,2, \ldots, k and \; (dst_i, dst')$
$for \; j = 1,2, \ldots, k \; are \; added \; to \; the \; layered \; graph$

VII. CONCLUSION

In this paper we have presented mathematical models to calculate optimal dynamic routes which are survivable against multi-Layer failure, assuming the Network Description Language to navigate the algorithm. In our next approach we will come out with a new Network status descriptive language that specifies a various underlying multilayers.

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