Designing Multi-Layer Provider Networks for Circular Disc Failures

Aniruddha Kushwaha[#], Deepak Kakadia[*], Ashwin Gumaste[#] and Arun Somani[^]
[#] Dept. of CSE, Indian Institute of Technology, Bombay, Mumbai, India.
[*] Access – Network Performance Group, Google, Mountain View USA.
[^] Dept. of ECpE, Iowa State University, Ames, USA.
Email: aniruddha@cse.iitb.ac.in, dkakadia@google.com, ashwing@ieee.org and arun@iastate.edu

***Abstract*—We examine the issue of disaster recovery after zonal outages in core networks, especially IP-over-WDM multi-layer networks. In particular, we consider the network design problem for a regional failure of circular area of radius *R*. Our goal is to design a network that can withstand a randomly located single failure of radius *R*. To this end, we formulate the problem as a constrained optimization problem whose solution for both IP-over-optical networks and pure ROADM-based networks is proposed. Subsequently, we develop an efficient heuristic based on a divide and conquer strategy that gives acceptable results. We also discuss the role of SDN in design and restoration of such networks. Simulation results are showcased over a core network topology thereby realizing the plausibility of such network design.**

I. Introduction

Fault tolerance is an important aspect of wide area networks [1]. Perhaps it is appropriate to say that fault tolerance is the most critical aspect of infrastructure operations on which public services are provisioned [2]. From a telecommunications perspective, node and link failures summarize much of outages. A spectrum of techniques have been developed for protection and restoration of services in the telecommunication domain. Much of these techniques propose 50-millisecond restoration of service post a failure. Complex provider networks are being investigated for node and link failure and a spectrum of protection strategies have been developed towards mitigating node and link failures in mesh networks [3]. Ranging from full capacity per-link 1+1 protection to shared risk link groups (SRLG) [3,4], the protection schemes mostly consider single event outages in networks. These kind of architecture failures are common, though their occurrence is usually not singular. In many of modern provider networks, failures are sizable in numbers and one can map these across different network strata. Such kind of multi-layer protection models are also widely investigated [4,5].

Apart from node and link failure is the issue of mitigating natural and man-made disasters that can take down portions of the network. Unlike network and link failures (which are significantly localized), *disc failures* (implying that an entire region is down) are more difficult to handle [6]. In the case of node and link failures, the failures are often independent of each other implying that two nodes may fail without necessarily having the same set of reasons for the failure. However, in the case of natural or man-made disasters (such as hurricanes, terror-attacks etc.) an entire region is likely to be impacted, which may involve several links and nodes being rendered non-functional. Restoration of a network after an entire region is down is termed as disc protection [7] on account of the approximate circular region (a city or a metropolitan region) that is likely to be impacted during a disaster.

In this paper, we assume a randomly located disc failure of size R. Clearly, we do not know where the failure may occur. Our assumption has the following rationale: in case of both natural and man-made disasters, we want to be able to certify a network to be able to cater to disasters of a certain magnitude. We do want to benchmark a network the worst-case failure such as a natural disaster of Category 5 hurricane or an earthquake of 7 on the Richter scale and man-made disasters of a thermonuclear weapon or a cyberattack on a regional grid [8]. To this end, we want to design a network such that a disc failure of radius R is taken care of by the network design itself – that is to say that post the failure of disc size R, the remaining nodes in the network would continue to be operational.

In section II, we summarize some of the related work pertinent to our disc protection problem. Section III describes the formulation of constrained optimization model that is instructive to the network design problem. Section IV describes an efficient heuristic for network design, which for small-sized networks is fast and gives promising results. Section V describes the impact of SDN on disc protection, while section VI showcases results from a simulations setup and section VII summarizes the paper.

II. Related Work

The area of protection and restoration has been considered by many researchers in the past and there is a rich body of literature available [9,10]. For optical networks, the first body of work revolved around the SONET/SDH concepts of 1+1 and 1:1 protection [9]. Subsequent to these were optical layer protection techniques using wavelength protection. The classical routing and wavelength assignment problem was extended to include protection in [11]. Multi-layer protection was considered in [12,13]. Edge-disjoint wavelength protection and its scope was considered in [14]. A key improvement in protection techniques was the formulation of the Shared Risk Link Group problem in [3]. Improvements of the SRLG problem were considered by many researchers such as [15].

The work that is closest to our work was described in [6]. In that approach, a graph-based approach towards modeling random cuts was developed. The value of that work lies in the computation of geometric probability to random cut lines

978-3-903176-07-2

leading to reliability computations. The same authors in [16] have extended their work to include max-flow min-cut based approach for disc failures. Our work is different from these efforts in the sense that we consider network design of a known set of nodes and plan on route optimizations without subjecting to traffic variances for a random failure of size R. We consider the network design problem from the practical perspective of ROADM design as well as IP routers and the impact on the number of transponders and line cards. Our solution is practical as it directly considers network equipment. We also consider a variation of the solution by including SDNs.

TABLE 1: PARAMETERS

$G(V,E)$	Network graph of set of V nodes and set of E edges
R	Radius of the disaster zone.
$Dz^r(v,e)$	Disaster zone of radius R covering v nodes and e edges in $G(V,E)$
$G'(V',E')$	Network graph after disaster having set of $V' = V \setminus v$ nodes and set of $E' = E \setminus e$ edges.
$G_{opt}(V,E)$	Optimized network graph for protection from a disaster of radius R.
E_{ij}, E'_{ij}	Edges between the node i and node j in the graph.$\forall i,j \in \{1,2,3 \ldots N\}$
T_{abkm}	m^{th} instance of the traffic request between source node a and destination node b using k^{th} path
$T_{abkm}(B)$	Bandwidth required for traffic T_{abkm}
PM^m_{abk}	Set of primary links (edges) on k^{th}path between source node V_a and destination node V_b for traffic T_{abkm}.
$PM^{m'}_{abk}$	Set of protection links (edges) on k^{th} path between source node V_a and destination node V_b for traffic T_{abkm} .
$\lvert PM^m_{abk}\rvert$, $\lvert PM^{m'}_{abk}\rvert$	Number of links on the k^{th} path of traffic T_{abkm}
PS_{ab}	Set of K paths sorted in increasing order of the path length
l_{ij}	Link between node V_i and V_j
Bw^k_{av}	Available bandwidth on the k^{th} path
Bw_{ij}	Available bandwidth on link l_{ij}.
C_{ij}	Total capacity of the edge E_{ij}
R_{ij}	It is the number of additional links/ports require for provisioning the protection path over the edge E_{ij}
δ_{ij}	Delay over the link l_{ij}. (link delay + processing delay of node i)

III. OPTIMIZATION MODEL FOR NETWORK DESIGN

Our goal is to build a network that would protect against a randomly located disc failure of some size R occurred due to natural or man-made disasters. Our fundamental assumption is that we do not know which region or disc in the network is likely to fail. However, for sake of classifying a network in terms of ability to be resilient, we would certify a network design to be capable of restoring against a failure of some disc radius R and hence want to come up with a dimensioning model for equipment that can restore services post a disc failure. Hence, we develop a model to compute the additional resources required to restore services in a network of a known topology with a randomly located disc failure of size R. This model would be developed considering practical provider deployments in core and metro networks into consideration.

We assume an optical core that supports WDM technology with Reconfigurable Optical Add Drop Multiplexers (ROADMs) [17], subtending wavelengths into optical fibers. The goal of the optimization model is to reduce the additional resources required (to increase the ROADM pass-through and add/drop ports) that would enable restoration of services post a random disc failure. Since, additional resources directly impact the CapEx (Capital Expenditure) in planning a provider's network our work directly helps a network provider to plan and protect the network based on projected traffic requirements.

TABLE 2:SYSTEM CONSTANTS

N	Number of edges $\lvert E\rvert$
l_{bw}	Maximum bandwidth of a wavelength
Δ	Maximum permissible delay
W_n	Number of wavelengths at each link
t	t^{th} Wavelength in set $\{1,2,3,\ldots,W_n\}$
t'	t^{th} Wavelength in set $\{1,2,3,\ldots,2*W_n\}$

TABLE 3: DECISION VARIABLES

Sw_i	Size of the electrical switch at node V_i
W_{ij}	Number of wavelength used at the link ij
$l^{ij}_{abkm}, l^{ij'}_{abkm}$	Link ij for traffic request T_{abkm}
P_{abkm}	$\begin{cases}1 \text{ if primary path for traffic } T_{abkm} \text{ exist in } G', \\ 0 \text{ otherwise.}\end{cases}$
P'_{abkm}	$\begin{cases}1 \text{ if protection path for traffic } T_{abkm} \text{ exist in } G', \\ 0 \text{ otherwise.}\end{cases}$
$\lambda^t_{abkm}, \lambda^{t'}_{abkm}$	$\begin{cases}1 \text{ if traffic } T_{abkm} \text{ is provisioned over the wavelength t,} \\ 0 \text{ otherwise.}\end{cases}$
$\lambda^{tij}_{abkm}, \lambda^{t'ij}_{abkm}$	$\begin{cases}1 \text{ if } \lambda^t_{abkm} \text{ or } \lambda^{t'}_{abkm} \text{ is provisioned over link ij ,} \\ 0 \text{ otherwise.}\end{cases}$

<u>*Optimization model:*</u> In our model, we assume a graph $G(V,E)$, of a set of V vertices and E edges extracted from the network topology. We compute the auxiliary graph $G'(V',E')$ by removing the nodes and edges from $G(V,E)$ present in the disaster region of radius R. Since, a disc failure can occur at any geographic location, but to include the disc failure of an arbitrary location in our optimization model, we require the exact node and edge locations which makes the optimization model complex. Therefore, we relax this requirement by assuming the nodes in the network graph G as the center of the disc failures, which actually represents the worst-case of impact post a failure of radius R. The key notations of our constrained optimization model are shown in Tables 1-3. The result of the optimization leads to ROADM/switch size dimensioning required at each node in G, in order to circumvent a circular disc failure. Since the ROADM/switch size depends on the number of wavelengths/links, therefore we model to minimize the number of wavelengths in the network with protection as our objective.

Objective: Our objective is to minimize the average number of wavelengths thereby minimizing the average switch size of the network with protection.

$$\min \frac{1}{N} \sum_{\substack{\forall E_{ij} \\ \forall abkm}} \sum_{\forall t'} \lambda^{t'ij}_{abkm}$$

The above objective function is valid for both ROADMs as well as L2/L3 switches or routers. In the case of switches and routers, the number of ports needs to be minimized. Further, since we are assuming a core network, this means that the number of ports is linearly proportional to the number of wavelengths with the caveat that we do not consider wavelength continuity for a pure IP network or one that allows wavelength conversion through electrical means facilitated by a controller (described later).

Our optimization model is subject to the following constraints:

Path Provisioning constraint: Equation (1) ensures that the primary and protection path does not share any node and link, i.e. node and link disjoint.

$$PM_{abk}^{m} \cap PM_{abk}^{m'} = \emptyset, \forall a,b \in V \quad (1)$$

Capacity constraint: Equation (2) gives the total capacity of the edge E_{ij} by multiplying the number of wavelengths and the bandwidth of the wavelength. Equation (3) and (5) ensures that the total traffic provisioned over an edge does not exceeds the total capacity of the edge. Equation (4) and (6) ensures that a single wavelength is assigned to a traffic request over an edge.

$$C_{ij} = W_n . l_{bw}, \forall E_{ij} \quad (2)$$

$$\sum_{\forall t,a,b,k,m} T_{abkm}(B).\lambda_{abkm}^{tij}.l_{bw} \leq C_{ij}, \forall E_{ij}, \forall t \quad (3)$$

$$\sum_{t=1}^{W_n} \lambda_{abkm}^{tij} \leq 1, \forall abkm, \forall E_{ij} \quad (4)$$

$$\sum_{\forall t,a,b,k,m} T_{abkm}(B).\lambda_{abkm}^{t'ij}.l_{bw} \leq C_{ij}, \forall E'_{ij}, \forall t \quad (5)$$

$$\sum_{t=1}^{2*W_n} \lambda_{abkm}^{t'ij} \leq 1, \forall abkm, \forall E_{ij} \quad (6)$$

Protection constraint: The constraints in equations (7) and (8) identifies whether the primary or protection path exist for traffic T_{abkm} after the occurrence of disaster.

$$P_{abkm} = \begin{cases} 1, \text{if } \sum_{i,j\in V'} \sum_{t}^{Wn} \lambda_{abkm}^{tij} = |PM_{abk}^{m}| \\ 0, \text{otherwise.} \end{cases}, \forall T_{abkm} \quad (7)$$

$$P'_{abkm} = \begin{cases} 1, \text{if } \sum_{i,j\in V'} \sum_{t}^{Wn} \lambda_{abkm}^{t'ij} = |PM_{abk}^{m'}| \\ 0, \text{otherwise.} \end{cases}, \forall T_{abkm} \quad (8)$$

$$P_{abkm} + P'_{abkm} \geq 1, \quad \forall T_{abkm}, \ \forall a,b \in V' \quad (9)$$

Constraint in equation (9) ensures that for a disaster of radius R occurring anywhere in the network, at least one path is available for the traffic T_{abkm} between node V_a and node V_b.

Wavelength Continuity: Equation (10) and equation (13) ensures that a wavelength is assigned to the primary and protection path. Constraints in equation (11) and equation (14) ensures that only single wavelength is assigned for a traffic request T_{abkm}.

$$\sum_{\forall abkm} T_{abkm}(B).\lambda_{abkm}^{t} \leq l_{bw}.l_{ij} \ \ \forall l_{ij} \in PM_{abk}^{m}, \forall abkm, \forall t \quad (10)$$

$$\Sigma\lambda_{abkm}^{t} \leq 1, \forall abkm, \forall t \quad (11)$$

$$\lambda_{abkm}^{tij} \leq \lambda_{abkm}^{t}, \forall l_{ij} \in PM_{abk}^{m}, \forall abkm, \forall t \quad (12)$$

$$\sum_{\forall abkm} T_{abkm}(B).\lambda_{abkm}^{t'} \leq l_{bw}.l_{ij} \ \ \forall l_{ij} \in PM_{abk}^{m'}, \ \forall abkm, \forall t' \quad (13)$$

$$\Sigma\lambda_{abkm}^{t'} \leq 1, \quad \forall abkm, \forall t' \quad (14)$$

$$\lambda_{abkm}^{t'ij} \leq \lambda_{abkm}^{t'} \ \forall l_{ij} \in PM_{abk}^{m}, \forall abkm, \forall t' \quad (15)$$

Delay Constraint: Constraints in equation (16) and (17) ensures that the total delay over a primary and protection path is within the permissible limit.

$$\sum_{\forall l_{ij}\in PM_{abk}^{m}} \delta_{ij} \leq \Delta, \qquad \forall a,b,k,m \quad (16)$$

$$\sum_{\forall l_{ij}\in PM_{abk}^{m'}} \delta_{ij} \leq \Delta, \qquad \forall a,b,k,m \quad (17)$$

The constrained optimization problem can be mapped to the 2-dimensional bin-packing problem and is hence NP-complete. For large networks or for dynamic traffic requests, an efficient heuristic is needed.

IV.HEURISTIC ALGORITHM

We propose a heuristic algorithm to configure the optimal network and ROADM/switch size such that in case of any disc failure of radius R in the network, the protection path always exists for a traffic originating and subsiding from outside of the disc failure zone. The proposed heuristic takes the network graph $G(V,E)$, ROADM/switch size Sw_i, disc radius R and traffic requests T_{abkm} as input and returns the superimposed network graph covering the protection path for all the affected traffic in disc radius R anywhere in the network.

Algorithm to find the optimal network graph for protection of disc failure of radius R

Input: G(V, E), Δ, δ, Sw, R, T_{abkm} $\forall a,b \in V$
Output: $G_{opt}(V,E)$ for $\forall V$
Compute primary path PM_{abk}^{m} for $\forall T_{abkm}$
Provision PM_{abk}^{m} for $\forall T_{abkm}$
    $Bw_{ij} = Bw_{ij} - T_{abkm}(B)$ where $E_{ij} \in PM_{abk}^{m}$
$\forall i,j = 1,2,3 \dots N$

For x in range (V):
    $Dz_x^r(V_d, E_d)$ is a subgraph of $G(V,E)$ having nodes and edges of V and E in a circle of radius R centered at node x.
    $G'(V',E') = G(V,E)/Dz_x^r(V_d,E_d)$

    For $\forall abkm$ in (T_{abkm})
        If $PM_{abk}^{m} \not\subset G'(V',E')$
            $(G_{opt}(V,E), BW, Sw)$
                $= PROVISION\_BACKUP((G'(V',E'), T_{abkm}, Bw, Sw, \Delta, \delta))$
            $G'(V',E') = G'(V',E') \cup G_{opt}(V,E)$
    $G(V,E) = G(V,E) \cup G'(V',E')$
Return $G(V,E), Sw$

To find the optimized network graph, we first calculate the primary path in the graph $G(V,E)$ for all the traffic requests. Traffic requests are provisioned over the corresponding calculated primary paths, if the bandwidth available over the path to accommodate the requested traffic. The algorithm deducts the bandwidth provisioned from the links along the path and only residual bandwidth remains for further provisioning. Since, the location of the disc radius is not known, we calculate the graph $z_x^r(V_d,E_d)$, where V_d are the nodes and E_d are the edges of $G(V,E)$ in the disc failure of radius R centered at node

$x: \forall x \in V$. We create a new auxiliary graph $G'(V',E')$ by removing the common nodes and edges of $z_x^r(V_d,E_d)$ and $G(V,E)$. Now, we compute all the primary paths provisioned in the previous step. If a path does not exist in the new graph $G'(V',E')$ then we invoke *PROVISION_BACKUP* (explained later) by passing the auxiliary graph $G'(V',E')$, the traffic request, the bandwidth and the ROADM/switch size to the *PROVISION_BACKUP* module. The call procedure *PROVISION_BACKUP* calculates and provisions the protection path in $G'(V',E')$ and if needed also adds extra wavelengths by adding an edge in the graph and/or increasing the switch size. The module *PROVISION_BACKUP* returns the graph $G_{opt}(V,E)$ which has the additional wavelengths as the edge of the graph. Thereafter, we superimpose all the $G_{opt}(V,E)$ in $G(V,E)$ to get the final graph.

Algorithm to provision backup path

Input: $G'(V',E'), T_{abkm}, Bw, \Delta, \delta$
Output: $G_{opt}(V,E), BW$
Compute all path PM_{abk} for traffic T_{abkm} in G', $k = \{1,2,3,\ldots,K\}$
PS_{ab} is the set of K paths sorted in increasing order of the path length.
Path provisioned = 0
For t in range K:
 $BW_{av}^t = \min(\{BW_{ij}\})\ E_{ij} \in PS_{ab}(t)$
 Delay=sum(δ_{ij}) where $E_{ij} \in PS_{ab}(t)$
 If Delay < Δ
  If $BW_{av}^t > T_{abkm}$
   Provision backup path using $PS_{ab}(t)$
   $Bw_{ij} = Bw_{ij} - T_{abkm}$, *where* $l_{ij} \in PS_{ab}(t)$
   Path provisioned = 1
   Break;
If Path provisioned = 0
 #We consider that delay is always in permissible limit for $PS_{ab}(0)$
 For all l_{ij} in $|PS_{ab}(0)|$:
  If $Bw_{ij} < T_{ab}$
   $Bw_{ij} = Bw_{ij} + \left\lceil \frac{T_{abkm}}{l_{bw}} \right\rceil$
   $E'_{ij} = E'_{ij} + \left\lceil \frac{T_{abkm}}{l_{bw}} \right\rceil$
   $Sw_i = Sw_i + \left\lceil \frac{T_{abkm}}{l_{bw}} \right\rceil$
   $Sw_j = Sw_j + \left\lceil \frac{T_{abkm}}{l_{bw}} \right\rceil$
 Path provisioned = 1
Return $G'(V',E')$, Bw, Sw

We also use *PROVISION_BACKUP* to calculate and provision a path. The module computes all the possible paths for a given traffic request in the graph $G'(V',E')$. All the calculated paths are sorted and stored based on their path length. For provisioning the traffic request, all the paths are checked for available bandwidth in the sorted order. In case traffic requests cannot be provisioned on shortest paths, then the next shortest path is evaluated for bandwidth availability. We do so by examining the link of the next shortest path that can suffice for our required bandwidth. Once we find the next shortest feasible path, we provision the traffic by deducting the bandwidth from all the links along the path. In case the available bandwidth over all the paths is not sufficient to provision the traffic request, then extra edges are added in the graph and the ROADM/switch size at the node is increased. This updated graph is provided as the output of the heuristic along with the link bandwidths and ROADM/switch size.

We run multiple iterations of the optimization model and heuristic by considering a different node as center of the disc failure of radius R in each iteration for a particular traffic profile. After running the iterations for all the nodes, we superimpose the additional wavelength requirement of each iteration in the graph G. The result is a network G that is able to protect against a failure of disc size R occurring anywhere in the network.

V. SDN AND DISC PROTECTION

Software defined networking involves the separation of data and control plane with a centralized controller orchestrating the network and planning/provisioning services across a network. The role of SDN in the case of designing networks with disc failures is relegated to traffic routing and equipment optimization. In particular, an SDN controller can plan for optimizing traffic placement across the network post a disc failure. An SDN controller routes traffic based on its atomicity level – i.e. coarse or fine chunks of traffic depending on the controllers' orchestration level are routed along same or different paths thereby optimizing the network. This leads to lower-sized requirements of the equipment in the network – nodes which would be subject to maximum traffic impact post a failure now can potentially be relieved of some of the impact due to better load balancing (post failure). It can hence be said that to design multi-layer network that are robust against disc failures an SDN controller is significantly helpful, if not mandatory. The SDN controller runs the optimization algorithm and comes up with an inventory list for each node. The network is thereafter designed taking into considerations the impact of the SDN controller. In our scheme, when we assume an SDN controller, we drop equations (10-13) on wavelength continuity constraint, thereby facilitating packet-level granularity to be juxtaposed on the network. By doing so (dropping equation 10-13) we are now able to assume that the SDN controller can optimize the traffic routing with respect to disc failures by appropriate sizing (dimensioning) of optical and IP router/switch nodes.

VI. SIMULATION AND RESULTS

In this section, we evaluate the path disrupted by a given disaster of radius in a 30-node core network topology. An optimization model was developed in Gurobi 7.5 with Python support. A separate Python code for the heuristic was developed as a discrete event simulation model. It takes around 20 minutes to run the optimization model in Gurobi running over Linux at HP ProLiant DL380p Gen9, 32GB RAM, 2.9GHz Xeon base server for a given disaster radius and traffic in the network and for a single iteration.

A. Network Model for Evaluation

For the evaluation of our optimization model and the heuristic, we used the network as shown in Fig. 1, which has 30-nodes, 36-links and average nodal degree of 2.4. For a given average hop size, we randomly select source and destination nodes to generate the traffic request in the network. Since the number of wavelengths on a link/edge can give the information about the size of the ROADM/switch, we simulate the model to find the average number of wavelengths used per link. In case the network consists of electrical switches/routers, all the wavelengths can be considered identical and each wavelength adds towards the port-count of the switch. In case of an all-optical network, wavelengths add towards the port-count of the ROADM at each node. For generating the traffic requests in the network, we assume that all the links in the network carry the same number of wavelengths and all the links are bidirectional. We consider load computation in the network to be proportional to the number of edges, number of wavelengths and averaged over the hop count over all source-destination pairs. Further, we assume ROADMs to be of at the most 4-degree.

Fig. 1. 30-Node Network topology [18]

In each of our results we consider 20-100 wavelengths with wavelength capacity 10Gbps with services ranging from 10Mbps to 1Gbps selected randomly. Same result is valid for higher wavelength capacity i.e. 100Gbps, as traffic request will be in proportion of wavelength capacity.

It is important to note that the results shown here represent the ROADM/switch size per degree of the node.

B. *Optimization and Heuristic Results*

We analyze the impact of the load on the average ROADM/switch required to protect the network for a disc failure radius of 50 km (typical metropolitan region) for different wavelengths scenarios as shown in Fig. 2. Here, we consider the average hop-length=4 for the traffic generation. From the results, it can be observed that at low loads < 20%, there is no need to deploy additional wavelengths as the wavelengths present already have enough bandwidth to carry the extra traffic in case of disc failure. As we start increasing the load >20%, there is a linear increase in the ROADM/switch size. At high loads > 80%, the required ROADM/switch size starts getting saturated. This behavior is due to the fact that the extra wavelengths added at the load of 80% are not fully utilized and the residual capacity across all the wavelengths is sufficient to accommodate the traffic for load >80%. This result is beneficial for a provider to plan and deploy additional capacity in its network, based on the maximum active load in the network at any given point of time. It is key to note that the heuristic performs well – almost within 15% of the optimal – which is surprising and can only be attributed to the fact that the network size we consider is a small network i.e. 30 nodes. The divergence between the heuristic and optimal would be significant for a large network, say of size 500 nodes, which though is not a typical core network scenario.

We analyzed the impact of the disc radius on the ROADM/switch size requirement as shown in Fig. 3. It is interesting to note that with increase in the disc radius, required ROADM/switch size are either same or it decreases slightly across all the different wavelength scenarios. This behavior can be attributed to the fact that with increase in the disc radius, larger part of the network goes down. As a result, active load in the network gets reduced and already available wavelengths are sufficient to carry the extra added load due to disc failure. This result was found to be valid in both the north-east US as well as Florida peninsula, where nodes are somewhat closer to each other. The importance of this result is that it is useful to benchmark a network against a catastrophe.

We also analyze the impact of the average hop size on the required ROADM/switch size as shown in Fig. 4. It can be observed that for all the wavelength scenarios, there is a linear decrease in the required ROADM/switch size with increase in the average hop length. It can be seen from the result that for an average hop-length of 10, the required ROADM/switch size reduces by ~25% of the size required at average hop length of 2. This is due to the fact that total traffic in the network will be more for the smaller average hop length as compared to the a larger average hop length network. Since, same traffic consumes the bandwidth over multiple hops in larger hop-length network. As a result, a network with higher average hop-length will require less number of additional wavelengths. This result is beneficial for a provider to avoid huge investment incurred in deployment of additional wavelengths when

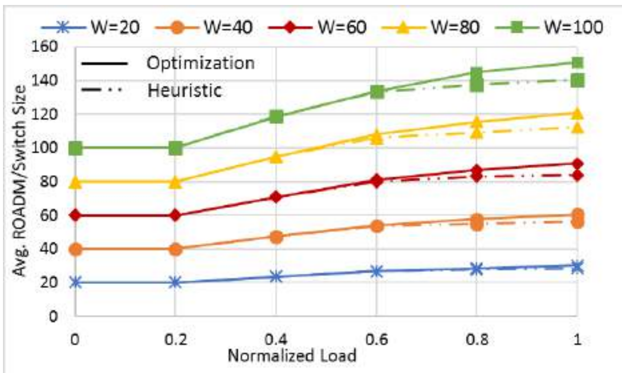

Fig. 2. Effect of load on the ROADM/switch size per nodal degree

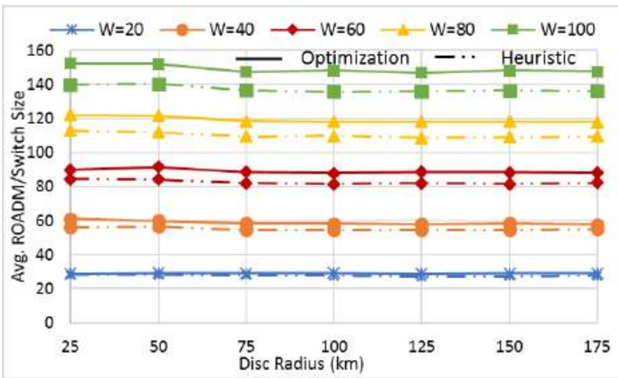

Fig. 3. Impact of disaster radius on the ROADM/Switch size

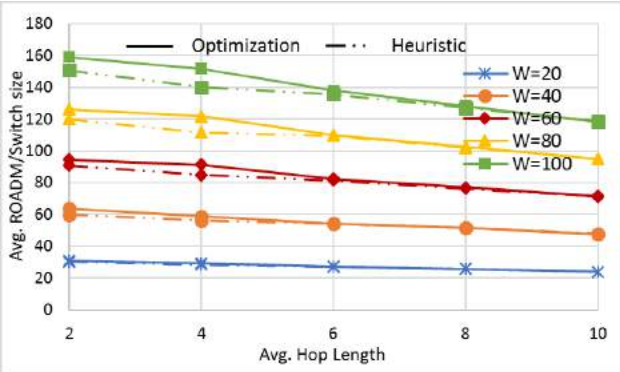

Fig. 4. Impact of the Average hop length on ROADM/Switch size

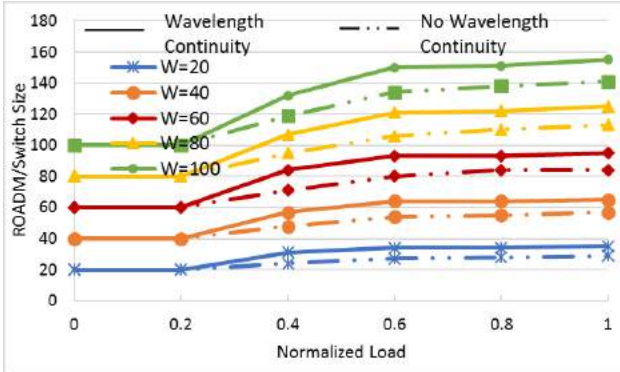

Fig. 5. Effect of wavelength continuity on the ROADM/Switch size

average traffic hop-length is larger in its network.

We also analyzed the impact of wavelength continuity on the ROADM size by adding the constraints in our heuristic model. Shown in Fig. 5 is the effect of the wavelength continuity on the ROADM/switch size. It is observed that addition of the wavelength continuity constraint increases the average ROADM size as compared to the average switch size required without employing the wavelength continuity. This increase in the size is because with no wavelength continuity there is flexibility of choosing a different wavelength at each link of the path. As a result, in case a single wavelength is not available for a traffic request, different wavelengths are selected for each link of the path. With wavelength continuity, a traffic request is provisioned by selecting a single wavelength over all the links in the path. There is possibility that bandwidth required to provision a traffic request is already available on all the links of the path but on different wavelengths, due to unavailability of a single wavelength to provision traffic request a new wavelength is added. As a result, the required ROADM/switch size is increased. This result is important for providers that want to deploy SDN in their networks. The role of an SDN controller would be that of a traffic shaper across the network. This is possible only when the wavelength continuity constraint can be relaxed and traffic at finer granularities can be offered to be provisioned across routes.

VII. Conclusion

In this paper, we have considered the important problem of network design post a failure of a disc of radius *R*. We have formulated this problem as a constrained optimization problem for both optical and IP networks. We have also considered the impact of an SDN controller on this problem. Further, an efficient heuristic is proposed that gives promising results (as compared to the optimal) for core networks. A simulation study validates our finding for different disc sizes, switch size evaluation and hop-length.

Acknowledgment

Aniruddha Kushwaha and Ashwin Gumaste are supported through DST, India. Arun Somani is supported through the Philip and Virginia Sproul Professorship at Iowa State University.

References

[1] D. Zhou and S. Subramaniam, "Survivability in optical networks," *IEEE Network*, vol. 14, no. 6, pp. 16–23, Nov.-Dec. 2000.
[2] J. Borland, "Analyzing the Internet collapse," *MIT Technology Review*, Feb. 2008. [Online]. Available: http://www.technologyreview.com/Infotech/20152/?a=f
[3] J. Doucette, WD Grover, "Capacity design studies of span-restorable mesh transport networks with shared-risk link group (SRLG) effects," SPIE Opticomm 2002, Boston Aug. 2002.
[4] R. Ramaswami and K. Sivarajan, "Optical Networks: A Practical Perspective," Elsevier, 3rd Edn. Morgan Kaufmann, 2010.
[5] L. Velasco, S. Spadaro, J. Comellas and G. Junyent, "ROADM design for OMS-DPRing protection in GMPLS-based optical networks," 6th International Workshop on Design and Reliable Communication Networks-2007, La Rochelle, France, Oct 2007
[6] S. Neumayer and E. Modiano, "Network Reliability With Geographically Correlated Failures," Proc. of Infocom 2010. San Diego, March 2010.
[7] A. Narula-Tam, E. Modiano, and A. Brzezinski, "Physical topology design for survivable routing of logical rings in WDM-based networks," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 8, pp. 1525–1538, Oct. 2004
[8] A Bernstein, D. Bienstock, D. Hay, M. Uzunoglu and G. Zussman, "Power grid vulnerability to geographically correlated failures — Analysis and control implications," In proc. of Infocom 2014, Toronto April 2014.
[9] A. Gumaste, T. Antony, "DWDM network designs and engineering solutions," Cisco Press, McMillan publishers, Dec. 2002.
[10] R. Ramaswami, K. Sivarajan, "Optical Networks: A Practical Perspective," San Mateo, Morgan Kaufmann, 2001
[11] J. Harmatos, P. Laborczi, "Dynamic Routing and Wavelength Assignment in Survivable WDM Networks," in Photonic Network Communications, 2002, Vol 4, No 3-4, pp. 357-376
[12] Q. Zheng and G. Mohan, "Multi-layer protection in IP-over-WDM networks with and with no backup lightpath sharing," in Computer Networks, Vol. 50, No. 3, pp 301-316 April 2006
[13] C. V. Saradhi, M. Gurusamy and L.Zhou, "Differentiated QOS for survivable WDM optical networks," IEEE Communications Magazine, Vol 42, No 5, pp. S8-14, May 2004
[14] C. Taunk, S. Bidkar, C. V. Saradhi, A. Gumaste "Impairment aware RWA based on a K-shuffle edge-disjoint path solution (IA-KS-EDP)," Optical Fiber Communication Conference and Exposition (OFC/NFOEC)-2011, Los Angeles, 6-10 March 2011.
[15] P. Datta and A. K. Somani, "Graph Transformation Approaches for Diverse Routing in Shared Risk Resource Group (SRRG) Failures," in Elsevier Computer networks Journal, Vol. 52, Issue 12, August 2008, pp. 2381-2394.
[16] S. Neumayer, A. Efrot and E. Modiano, "Geographic max-flow and min-cut under a circular disk failure model," Computer Communications 2015. Vol 77 pp 117-127
[17] Online: CDC ROADM Applications and Cost Comparison, OFC 2012. https://www.ofcconference.org/getattachment/188d14da-88ba-4a63-91d6-1cc14b335d8b/CDC-ROADM-Applications-and-Cost-Comparison.aspx
[18] Online: http://www.monarchna.com/topology.html