DRAMA: Disaster Management Algorithm with Mitigation Awareness for Elastic Optical Networks

Rujia Zou*, Hiroshi Hasegawa†, Suresh Subramaniam*
*Department of Electrical and Computer Engineering ,The George Washington University
{rjzou,suresh}@gwu.edu
†Department of Electrical Engineering and Computer Science, Nagoya University
hasegawa@nuee.nagoya-u.ac.jp

***Abstract*—Elastic optical networks (EONs) have emerged as attractive candidates for satisfying the huge demands being placed on transport networks by emerging 5G and cloud applications. EONs provide high spectrum utilization efficiency due to flexibility in resource assignment. Because of their extremely high capacity, EONs need sophisticated survivability mechanisms and disaster management schemes to prevent or mitigate the loss of data in the event of failures and large-scale disasters. Traditionally, disaster recovery has aimed to recover the traffic impacted by the disaster by re-assigning alternate resources to the traffic. Such recovery can potentially affect all the traffic in the network, including that which may not be close to the disaster. We propose a new approach to disaster recovery in this paper, wherein a mitigation zone is defined around the disaster zone. In our approach, only the traffic within the mitigation zone is affected by re-assignment of resources to disaster-impacted traffic, and traffic outside the mitigation zone is not affected. We propose an optimization problem to minimize the penalty due to service degradation after a disaster, and present a heuristic algorithm named Disaster Management Algorithm with Mitigation Awareness (DRAMA).Simulation results show that DRAMA has better performance than a recovery algorithm that does not consider mitigation, and a simple algorithm without service degradation in recovery.**

I. Introduction

Elastic optical networks (EONs) are considered a promising solution to satisfy the dramatic growth of network traffic due to the flexibility in resource allocation and spectrum assignment [1]. In EONs, network traffic is allocated bandwidth in terms of frequency slots (FS), each of which is 12.5 GHz wide [2]. A well-known resource assignment problem in EONs is the Routing and Spectrum Assignment (RSA) problem, which assigns routes and spectrum to service requests (lightpaths), while ensuring spectrum continuity and spectrum contiguity [3] [4].

Survivability is a crucial aspect of optical networks; typical survivability techniques can be divided into protection and restoration or recovery [5]. In protection strategy, backup resources are reserved before a network failure happens [6] [7]. For instance, p-cycle is a protection strategy which is very attractive due to fast and efficient recovery [8] [9] [10]. In this strategy, a set of pre-connected cycles is established, and a lightpath will be re-routed and switched to the p-cycle if the original lightpath is disconnected due to network failure. In recovery strategy, backup lightpaths are generated after a network failure happens. The "recovery" here refers to the recovery of traffic as opposed to network components.

A special case of survivability is disaster management. Survivability techniques are typically designed for small-scale failures such as a single failure or the failure of a small set of nodes and/or links. Disasters, such as earthquakes and hurricanes, may cause large scale damage to network infrastructure. It is typically cost-prohibitive to design protection mechanisms for all possible disaster scenarios because of the huge amount of redundant resources that would be needed. In this case, a recovery strategy has a lower redundancy since the recovery lightpath is assigned after a disaster [11] [12].

Disaster recovery in optical networks has been a subject of research recently. In [13], a network component recovery algorithm is proposed to maximize the traffic demand after disaster. In [14], a joint progressive recovery algorithm for a WDM (wavelength division multiplexing) network with datacenters is proposed to recover the network nodes and datacenters after large-scale disasters. However, traffic recovery is not investigated in these papers. In [11], a heuristic traffic recovery algorithm is proposed with genetic operator for EONs, where the genetic operator is used to optimize the serving order for failed services. The feasible ordering configurations are generated iteratively and solutions that increase the network recovery capability are retained.

In [12], a capacity-constrained maximally spatial disjoint lightpath algorithm is proposed for EONs. However, in these papers, services in the entire network, including those far away from the disaster location, are inevitably affected by the recovery.

In this paper, we propose a new approach to disaster recovery. Our approach is rooted in the intuition that services that are far away from the disaster zone should not be affected during the recovery process. To this end, we propose the concept of a *mitigation zone*, which is an area surrounding the disaster zone. In our approach, only the traffic within the mitigation zone is affected by re-assignment of resources to disaster-impacted traffic, and traffic outside the mitigation zone is not affected. We propose an optimization problem to minimize the penalty due to service degradation after a disaster. We have developed an Integer Linear Program (ILP), which can be solved for small problem instances, but do not present it here for space reasons. We present a heuristic algorithm named Disaster Management Algorithm with Mitigation Awareness (DRAMA) that can be used for realistic problem instances. Simulation results show that DRAMA has better performance than a recovery algorithm that does not consider a mitigation zone. The contributions of our work can be summarized as follows:

- The concept of mitigation zone is proposed for disaster recovery.
- An optimization problem for minimizing the penalty due to service degradation is defined, and an ILP is formulated.

- A heuristic algorithm, DRAMA, is designed for the re-assignment of affected traffic by choosing the appropriate degradation level and alternate resources.
- Simulation results show the effectiveness of DRAMA in terms of total penalty.

The rest of the paper is organized as follows. The disaster recovery problem is defined in Section II, and the proposed DRAMA algorithm is presented in Section III. Sample simulation results are given in Section IV, and the paper is concluded in Section V.

II. The Disaster Recovery Problem

The disaster recovery problem is defined as follows. Consider a network $G(N, E)$, where N denotes the set of optical cross-connects (OXCs) and E denotes the set of links; each link has a pair of fibers (in opposite directions). At the time of disaster, there is a set of ongoing lightpaths T with pre-assigned resources (routes, spectrum, modulation). A lightpath is denoted as $t(s, d, w)$, where s and d represent the source and destination nodes,[1] and w denotes the data rate. Each lightpath is assigned a unidirectional route with spectrum continuity and spectrum contiguity. There are several modulation formats corresponding to different spectrum efficiencies and different distance limitations, and a lightpath is assigned the highest modulation format possible for the length of its path.

The *disaster zone* is modeled as a circular area with center C_d and radius R_d, $D(C_d, R_d)$, and we assume that any link or node that (even partially) lies in the disaster zone is failed after the disaster. All the lightpaths that cross a failed node or link are assumed to be disconnected and need to be recovered. If there is no possible path from a lightpath's source node to its destination node after the disaster, the lightpath is considered to be unrecoverable.

Now consider the circular region with center $C_m = C_d$ and radius $R_d + R_m$. The *mitigation zone* $M(C_m, R_m)$ is defined as the annulus bounded by this circular region and the disaster zone. The area excluding the disaster and the mitigation zones is denoted by U.

Every lightpath $t \in T$ is considered be in one of the three zones – D, M, or U – depending on where their source/desitnation nodes lie. If the source and/or destination node lies within D, then we say $t \in D$; else if the source/destination lies within M, then we say $t \in M$; else, $t \in U$.

Clearly, any $t \in D$ is unrecoverable because its source/destination is unreachable. If $t \in M$ is not affected by the disaster (i.e., its path is not disrupted due to the disaster), then its path is not re-assigned, whereas if $t \in M$ is affected by the disaster (i.e., its path is disrupted), then its path must be re-assigned. In either case, the service can be degraded (i.e., data rata can be reduced) during recovery for $t \in M$. If $t \in U$, then its path is re-assigned if it is disrupted by the disaster, otherwise its path is not re-assigned. In either case, if $t \in U$, then it is recovered with its original data rate without service degradation; if this is not possible, then the lighpath t is dropped.

We explain these ideas with the help of an example in Fig. 1. Here, the center of the disaster and mitigation zones is node

[1] We assume that any OXC node can be a source or destination of lightpaths.

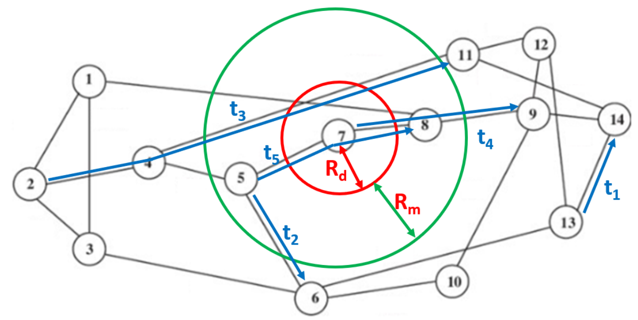


Fig. 1: Examples of traffic inside and outside the disaster and mitigation zones.

7. The disaster zone is the red circle and the mitigation zone is bounded by the red and green circles. Node 7, links 1-8, 4-11, 5-7 and 7-8 are disabled by the disaster. Nodes 5 and 8 are inside the mitigation zone. There are five lightpaths (LPs) t_1 to t_5 at the time of the disaster. LP t_1 is not affected by the disaster and is outside the mitigation zone, and so it will not be affected during disaster recovery. LP t_2 is not affected by the disaster but is inside the mitigation zone. LP t_3 is affected by the disaster but not inside the mitigation zone. LP t_4 is inside the disaster zone and is unrecoverable. LP t_5 is affected by the disaster and is inside the mitigation zone. LPs t_2 and t_5 can be re-assigned and recovered with degraded service, while LP t_3 must be re-assigned resources without service degradation since it is outside the mitigation zone.

Each LP brings revenue to the network operator. For simplicity, we assume that the revenue is equal to the data rate of the LP (arbitrary units) in this paper, though we can easily generalize to other revenue models. A non-decreasing penalty function $P(df)$ which is a function of the degradation factor df of an ongoing lightpath is also given. In this paper, we choose the penalty function shown in (1) and Fig. 2. This particular function is chosen so that the penalty is small for small degradation values and increases more quickly as the degradation increases. The penalty is 0 for no degradation ($df = 0$), and the denominator of (1) ensures that the penalty is 1 for no degradation. The penalty indicates the percentage of revenue lost when a lightpath's service is degraded. The degradation factor df is defined as the ratio of the decrease in data rate or loss of data rate of a lightpath to its original data rate, as given by (2). For instance, suppose a LP is inside the mitigation zone and the data rate is 400 Gbps with 16-QAM (50 Gbps/slot) modulation format, then the original number of slots is 8. Suppose the recovered lightpath after the disaster is provided with 6 slots with the same modulation format, then the degradation factor is (8-6)/8 = 0.25. According to (1), the percentage of revenue lost that corresponds to $df = 0.25$ is about 0.11. Therefore, recalling that the revenue is equal to the data rate, the absolute penalty in this case is 0.11 * 400 = 44. If a LP is blocked/dropped after the disaster, all the revenue is considered to be lost and the penalty is equal to the revenue.

$$P(df) = \frac{\log(1 - 0.9 \times df)}{\log(1 - 0.9 \times 1)} \tag{1}$$

$$df = \frac{\text{Loss of data rate}}{\text{Original data rate}}. \tag{2}$$

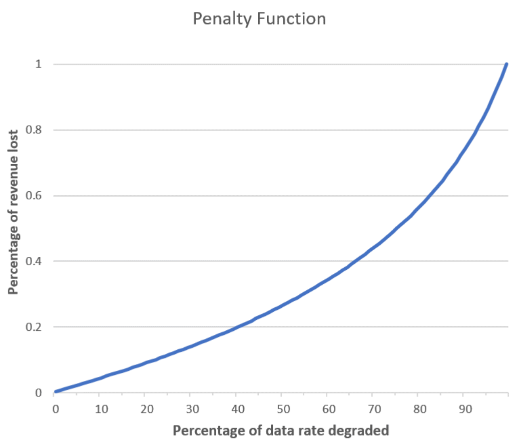


Fig. 2: The penalty function.

The objective of the disaster recovery problem is to accommodate the recoverable traffic (i.e., the lightpaths whose source and destination are not within the disaster zone) and minimize the total penalty. This is a very challenging problem and includes a number of sub-problems, many of which are known to be NP-hard. We break this problem into two sub-problems: one is to find appropriate degradation factors for all the traffic inside the mitigation zone, and the other is the Routing and Spectrum Assignment (RSA) problem for the recoverable traffic.

III. The DRAMA Algorithm

In this section, we describe the DRAMA heuristic algorithm. DRAMA first determines the order in which the traffic will be recovered, and then proceeds to determine the degradation factor and does RSA for the recovered lightpath.

A. Order of recovery

First, all the recoverable affected traffic and traffic inside the mitigation zone are sorted in terms of Revenue Efficiency (RE) in non-increasing order. The RE is defined as follows:

$$RE = \frac{\text{Revenue of traffic}}{\text{Minimum spectrum cost}}. \tag{3}$$

Here, the revenue is the revenue of the lightpath, and the minimum spectrum cost is defined as $Number\ of\ slots \times Number\ of\ hops\ on\ shortest\ path$. The number of slots is determined by the data rate of the traffic and highest modulation format possible for the shortest path. Lightpaths are considered for recovery in descending order of RE because these lightpaths have the highest revenue per unit spectrum cost. Note that the actual spectrum cost would depend on the actual path selected for recovery (which is not known yet), which may not necessarily be a shortest path. However, we use the quantity RE as a measure of the priority for recovering lightpaths after the disaster.

B. Recovery algorithm

We now describe the recovery algorithm that includes the determination of degradation factors and RSA for traffic inside the mitigation zone. The pseudocode of DRAMA is shown in Algorithm 1.

In lines 1-8, we release the spectrum of unrecoverable LPs and LPs that can be recovered but re-assigned. The LPs that can be recovered and re-assigned are added to set T'. In line 9, all the LPs in T' are sorted in decreasing order of RE, and each traffic is recovered one by one in this order.

The recovery and re-assignment are executed in lines 10-21. For the traffic outside the mitigation zone and affected by the disaster, the service is *not degraded*, i.e., its data rate is not reduced. The recovery is done using a shortest path (SP) on the surviving network and the First Fit (FF) algorithm is used for spectrum assignment. If spectrum is not available to recover the traffic fully, it is dropped, and the penalty is set equal to the traffic's revenue. This recovery procedure is shown in lines 11-12.

Algorithm 1 DRAMA Algorithm

Input: $G(N, E)$, T, $D(C_d, R_d)$, $M(C_m, R_m)$
Output: Degradation factor and RSA for recovered traffic
1: Initialize an empty traffic set T'
2: **for** each $t \in T$ **do**
3:   **if** $t \in D$ (i.e., t is unrecoverable) **then**
4:     Release the spectrum of t
5:   **else if** $t \in M$ **or** t's path is disrupted by disaster **then**
6:     Release the spectrum of t, add t to T'
7:   **end if**
8: **end for**
9: Sort all $t \in T'$ in decreasing order of RE
10: **for** each $t \in T'$ **do**
11:   **if** $t \notin M$ (i.e., t is affected by disaster, but $t \in U$) **then**
12:     Assign t with SP-FF RSA without degradation; block t if FSs not available
13:   **else**
14:     Determine the modulation format and number of FSs with SP
15:     **for** each possible degradation option **do**
16:       Calculate $PP = CP + FP$
17:     **end for**
18:     Select the degradation option that has the lowest PP
19:     Assign t with SP and FF with selected degradation; block t if FSs not available
20:   **end if**
21: **end for**

Lines 13-19 show the re-assignment procedure for the traffic inside the mitigation zone. Re-assignment is done no matter if the traffic is affected by the disaster or not. For each traffic, first we determine the number of slots needed without service degradation for the highest level modulation on the shortest path of the surviving network. Then, for each candidate degradation option, we calculate the Potential Penalty (PP), which is defined as the sum of the Current Penalty (CP) and Future Penalty (FP). (The calculation of PP is explained below.) The candidate with the lowest PP is then selected for the traffic. For instance, suppose there is a 400 Gbps traffic which is assigned 16-QAM; the number of slots needed without degradation is 8. Then, there are 9 candidate degradation options (0 to 8 slots for the recovered traffic). The option which gives the lowest PP is selected as the recovered traffic's data rate. Recall that the degradation factor is the ratio of decrease in a recovered traffic's data rate to its original data rate. After selecting the degradation factor, the traffic is assigned that amount of spectrum using SP-FF.

When an LP is considered for degradation, a lower penalty is incurred if it is recovered with a lower degradation factor. However, this causes less bandwidth to be available for the remaining LPs yet to be recovered. CP and FP are designed to balance this tradeoff. CP is calculated based on the current degradation option using the penalty function. For instance, if the same traffic (400Gbps, 16-QAM) is assigned 2 fewer slots, then CP is 44 (as shown in the example above Eq. (1)).

The FP of a candidate degradation option is calculated according to Algorithm 2. It is based on the network status if we assign the LP with this degradation option. We emphasize that this degradation option is not the final selection; it is only used to calculate the FP for this option.

Algorithm 2 Calculation of Future Penalty

Input: $G(N, E)$, t, SP p, a degradation option
Output: Value of Future Penalty (FP)
1: Assign the traffic with p, FF, and the given degradation option; initialize $FP = 0$
2: **for** each SP p' of an s-d pair that shares a link with p **do**
3: Initialize $ADR_{p'}$ and $RDR_{p'}$
4: **if** $ADR_{p'} \geq RDR_{p'}$ **then**
5: Calculate the basic penalty and add to $LFPp'$
6: **else**
7: Calculate the basic penalty and add to $LFPp'$
8: Initialize the PE of all the LPs waiting to be recovered or re-assigned on p' and sort them in descending order of PE
9: **while** $ADR_{p'} < RDR_{p'}$ **or** the number of degradation slots in this LFP calculation is $\geq$ the number of slots saved in current penalty **do**
10: Select the LP t' with highest PE
11: **if** $t \notin M$ **and** t affected by disaster **then**
12: Calculate the penalty of full degradation and add to $LFP_{p'}$
13: **else if** $t \in M$ **then**
14: Calculate penalty of 1-slot degradation and add to $LFP_{p'}$
15: **end if**
16: Update $RDR_{p'}$ = $RDR_{p'}-$ data rate corresponding to degradation in line 12 or 14
17: Update PEs of LPs
18: **end while**
19: **end if**
20: $FP = FP + LFPp'$
21: **end for**

In line 1, the recovery path p is assigned to the LP t with the given degradation option. Now, the assignment of spectrum to this LP will affect the spectrum availability (and hence the degradation) of future LPs (i.e., the LPs that are waiting to be recovered). We calculate the future penalty as the sum of the Lightpath Future Penalty (LFP) of all the shared LPs (i.e., the LPs that share a link of p).

The *Request Data Rate (RDR)* of a shared path p' is defined as the sum of data rates of LP requests that are waiting to be recovered or re-assigned on p'. The *Available Data Rate (ADR)* of a shared path p' is defined as the total data rate that is available on p', calculated using the number of available slots on p' times the data rate per slot, based on the highest modulation format available on p'. If the RDR is lower than the ADR, we first calculate the basic penalty of each waiting LP and add them to the LFP. If the LPs on p' are outside the mitigation zone and the waiting LP cannot be assigned in the current network state, the basic penalty is calculated as the blocking penalty (i.e., full degradation), otherwise, the basic penalty is 0. If the LP is inside the mitigation zone, the basic penalty is calculated by the best effort degradation case. For example, if a 400G LP requires 8 slots but the largest contiguous block of spectrum available is 6 slots, the basic penalty is $P((8-6)/8) * 400 \approx 44$.

If the ADR is lower than the RDR, then we need to calculate the penalty of degrading various LPs. In line 7, the basic penalty of each waiting LP is calculated and added to the LFP. Then, in line 8, we sort all the LPs waiting to be recovered or re-assigned on p' with the Penalty Efficiency (PE) in non-decreasing order (shown in line 8). The Penalty Efficiency is defined as follows:

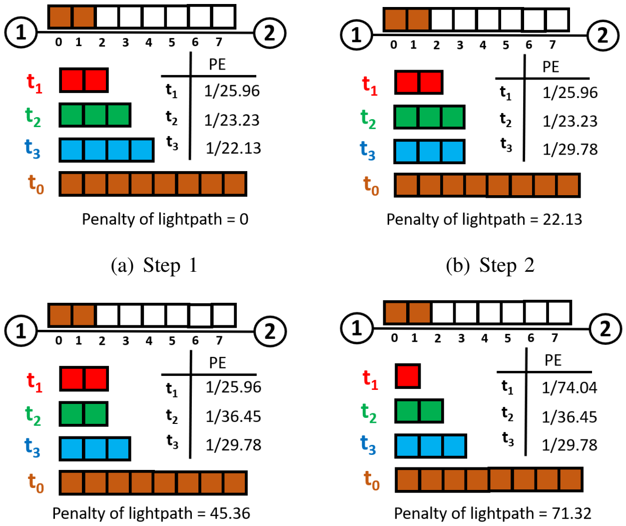
$$PE = \frac{Number\ of\ slots\ saved}{absolute\ value\ of\ penalty}. \quad (4)$$

If the LP is outside the mitigation zone, PE is initialized with all slots saved because it has to be either not degraded at all or blocked. If the LP is inside the mitigation zone, PE is initialized with 1 slot saved. For example, if an LP requires 8 slots and the largest contiguous block is 6 slots, the PE is initialized with 1 slot degradation, i.e., from 6 to 5 slots.

We keep doing the gradual degradation of the LP with highest PE until the RDR becomes less than the ADR, or the number of degradation slots in this step is not lower than the number of slots saved in current penalty (line 9). If the waiting LP with highest PE is outside the mitigation zone, the penalty of full degradation is added to the LFP (line 12). If the LP with the highest PE is inside the mitigation zone, it is degraded by 1 slot and the penalty of this 1-slot degradation is added to the LFP (line 14). The RDR is updated by taking this degraded data rate into account (line 16), and the PEs are recalculated for all the LPs (line 17). For the same example, if the LP that has the degradation from 6 to 5 slots has the highest PE, then the PE is updated as degradation from 5 to 4 slots, and the while loop continues.

An example of FP calculation is shown in Fig. 3, in which there are 4 LPs t_0, t_1, t_2 and t_3 with data rates 400 Gbps, 100 Gbps, 150 Gbps, and 200 Gbps, respectively. We assume that all the LPs are inside the mitigation zone and are between node 1 and node 2. The modulation format is 16-QAM (50 Gbps/slot), and therefore the required number of slots are for the four LPs are 8, 2, 3, and 4, respectively. Suppose we are selecting the degradation factor of t_0 and calculating the future penalty of LP t_0 in 6-slot degradation case. t_1, t_2, t_3 are waiting to be assigned. Slots #1-2 are assigned to t_0 and slots #2-7 are idle. The ADR is then $6 * 50 = 300$ Gbps.

The initialized PEs are shown in Fig. 3(a). For t_1, the value



(a) Step 1 (b) Step 2

(c) Step 3 (d) Step 4

Fig. 3: Examples of Future Penalty calculation on one lightpath

of PE is calculated with penalty of 1-slot degradation, i.e., from 2 to 1 slot. So, the degradation factor is 0.5 and using the penalty function (Eq. (1)), we get $P(0.5) = 0.2596$, and the absolute penalty as $0.2596 * 100 = 25.96$). In Fig. 3(a), t_3 has the highest PE and is degraded with 1 slot first. In Fig. 3(b), the PE of t_3 is updated with the penalty of 1 more slot degradation (the absolute penalty of 1-slot degradation − the absolute penalty of 2-slot degradation). In Fig. 3(c), the RDR is 350 Gbps but the ADR is 300 Gbps and since RDR > ADR, we continue with degradation. In Fig. 3(d), the SDR (300 Gbps) is not higher than the ADR (300 Gbps). Therefore, the future penalty of for t_0 on path $1-2$ in 6-slot degradation case is 71.32.

The worst-case complexity of DRAMA is $O(|N|^3 + |T|\log|T| \cdot |N|^2 \cdot F \cdot \epsilon)$, where N is the set of nodes, T is set of LPs before disaster, and F is the number of FSs per fiber. The first term is the complexity to determine shortest paths for all s-d pairs, and the second term captures the sorting of LPs according to PE, and ϵ is the maximum number of slots needed per LP.

IV. Simulation Results

We now present simulation results to demonstrate the effectiveness of the proposed DRAMA algorithm. The network topologies used are the COST239 network (11 nodes and 26 links, shown in Fig. 4) and the NSF network (14 nodes and 21 links shown in Fig.5). We assume 352 slots on each fiber.

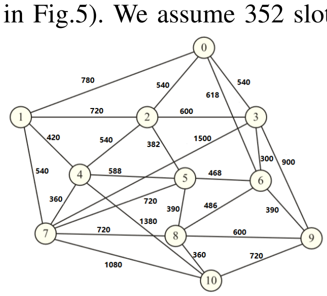


Fig. 4: 11-node COST239 network.

Before the disaster, a set of unidirectional traffic requests is generated with uniformly distributed source and destination

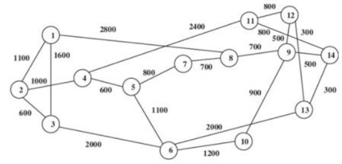


Fig. 5: 14-node NSF network.

nodes. There are three different types of requests with rate 40/100/400 Gbps (with probability 0.2, 0.5, and 0.3, respectively). The number of required FSs is determined by its data rate and modulation format. The following modulations are used: 16-QAM, 8-QAM, QPSK and BPSK. Table I shows the number of FSs corresponding to different data rates and different modulation formats. For each modulation format, the physical distance limitations are shown in Table II.[2] The required numbers of FSs for a given modulation format is calculated as follows:

$$F = \left\lceil \frac{w}{ModE_m} \right\rceil, \tag{5}$$

where F is the number of required FSs, w is the data rate of the traffic, $ModE_m$ is the spectrum efficiency of modulation format m (defined as data rate per FS) used for the traffic. For instance, the spectrum efficiency of BPSK is 12.5 Gbps.

2000 traffic requests are generated and assigned with minimum-spectrum-cost path among k-shortest paths ($K = 5$) and FF assignment; if none of the k-shortest path have available slots, the traffic will be blocked. Three different disasters are tested, as shown in Table III. 50 trials are conducted for each experiment, and 95% confidence intervals are plotted.

TABLE I: Required FSs for various data rates and modulations [7].

Modulation \ Date Rate	40G	100G	400G
16-QAM	1	2	8
8-QAM	2	3	11
QPSK	2	4	16
BPSK	4	8	32

TABLE II: Reach for different modulation formats [7].

Modulation	Transparent reach
16-QAM	500 km
8-QAM	1000 km
QPSK	2000 km
BPSK	> 2000 km

TABLE III: Disaster scenarios for experiments.

Center	Affected links
Node 7 in NSF	1-8, 5-7, 7-8, 4-11
Node 2 in NSF	1-2, 1-3, 2-3, 2-4
Node 6 in COST	0-3, 3-6, 5-6, 8-6, 9-6 ,3-9

Figs. 6 and 7 show the total penalty incurred by DRAMA (green bars) as a function of the difference in radii between the outer circle and the disaster zone circle that define the mitigation zone. For comparison, the penalty when there is no mitigation zone is shown as a dashed line. We make the

[2]We assume that there is no physical distance limitation for BPSK in order to guarantee that all the requests can be assigned to the network.

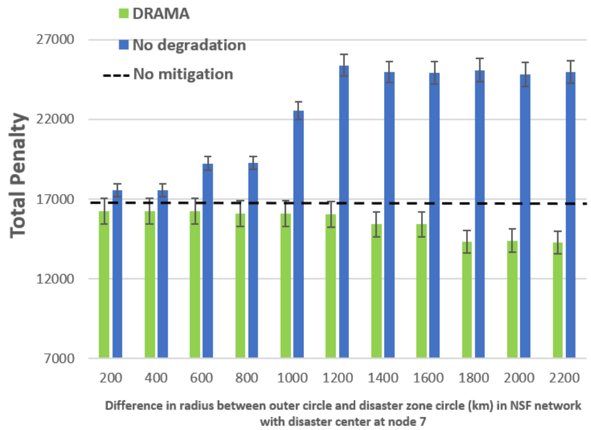


Fig. 6: Total penalty when disaster happens at node 7 in NSF network.

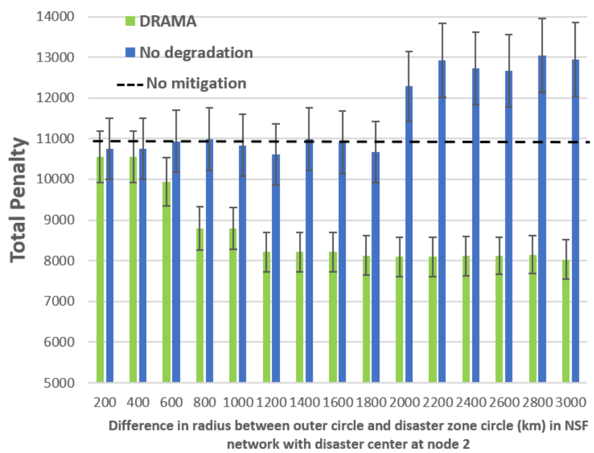


Fig. 7: Total penalty when disaster happens at node 2 in NSF network.

following observations. First, the penalty decreases significantly as the size of the mitigation zone increases (12.2% for 2200 km radius difference in Fig. 6, and 24.9% for 3000 km radius difference in Fig. 7). This shows the effect of providing flexibility to the recovery algorithm – the more that traffic far away from the disaster is willing to be degraded, the lower the penalty. Thus, there is a tradeoff between how widespread the disruption is (size of mitigation zone) and the recovery performance (penalty). We also see that the absolute penalty is much lower in Fig. 7 compared to Fig. 6. This is because node 7 is at the "center" of the NSF network and many LPs pass through it, and hence it is harder to recover traffic in this case. For the same reason, the decrease in penalty is not large as in Fig. 7 as the mitigation zone expands

We also show the performance of a naive re-assignment algorithm (blue bars) in which LPs eligible for re-assignment are selected for recovery in random order and assigned spectrum without degradation (or blocked if spectrum is unavailable). The figure shows that it performs very badly and cannot take advantage of the additional flexibility due to the mitigation zone; indeed, the performance becomes worse as the mitigation zone expands.

In Fig. 8, the total penalty when disaster is centered at node 6 in COST239 network is shown. The total penalty is lower than in NSFnet because of the smaller size of COST239, which result in higher level modulations and fewer FSs being used for the traffic. Therefore, it is easier to recover traffic in this network.

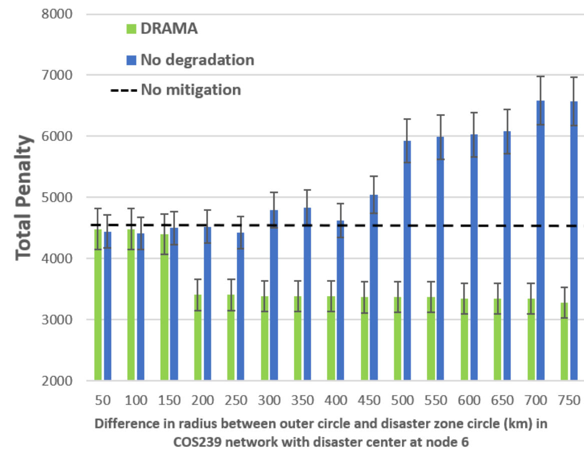


Fig. 8: Total penalty when disaster happens at node 6 in COST239 network.

TABLE IV: The distribution of ADFs when disaster happens at node 7 in NSFnet.

R	40G	100G	400G
200	–	–	–
400	–	–	–
600	–	–	–
800	0.339	0.383	0.438
1000	0.298	0.311	0.335
1200	0.279	0.245	0.264
1400	0.280	0.204	0.210
1600	0.280	0.204	0.210
1800	0.287	0.197	0.186
2000	0.305	0.194	0.175
2200	0.300	0.191	0.171

We show the distribution of average degradation factors (ADFs) for the three different types of traffic in Table IV for different values of difference in radii R (in km). The average ADFs are calculated among the LPs that are eligible for degradation.

In this table, the average number LPs before the disaster is about 926. There is no value for $R = 200, 400, 600$ because no node is located inside the mitigation zone and no traffic is inside the mitigation zone. As the mitigation zone expands, larger data rate LPs are provided with lower degradation factors because the large LPs incur more (absolute) penalty for the same degradation factor.

Finally, we examine the performance of DRAMA in terms of bandwidth blocking ratio (BBR) in Figs. 9 and 10. In Fig. 9, BR-No mitigation and BR-DRAMA are defined as the sum of data rates of blocked LPs (i.e., LPs that are dropped due to lack of spectrum) to the sum of data rates of recoverable LPs (i.e., LPs in the set T' of Algorithm 1). As we can see, the mitigation zone leads to a much lower BBR. Some LPs may be inside the mitigation zone but not directly affected by the disaster. These LPs are also candidates for re-assignment by DRAMA. The BBR of such LPs is also plotted in Fig. 9

as BR-DRAMA-TU. We note that such blocking is very low and DRAMA is effectively able to recover most of the traffic within the mitigation zone.

In Fig. 10, the BBR of LPs outside the mitigation zone (BR-TOMZ) is shown. BR-TOMZ-DRAMA is defined as the BBR of LPs that are outside the mitigation zone and affected by the disaster. BR-TOMZ-No Mitigation is defined as the BBR of the same LPs in BR-TOMZ-DRAMA since there is no mitigation zone in this case. The BR-TOMZ-DRAMA is lower than BR-TOMZ-No Mitigation and the difference increases with mitigation zone size. This result shows that the mitigation zone can also improve the recovery of traffic far away from the disaster. A lower BBR satisfies the motivation for DRAMA, i.e., traffic far away from the disaster is less affected.

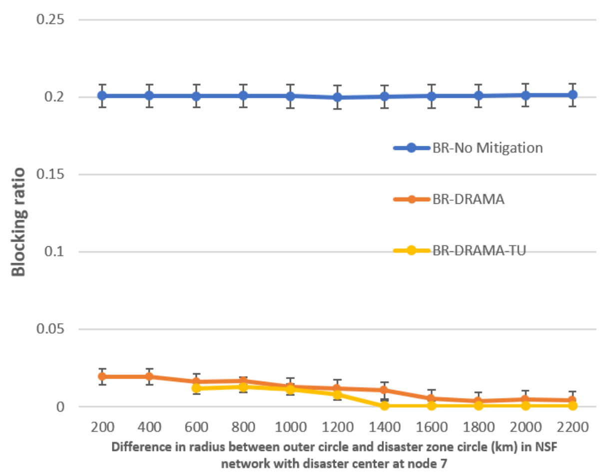


Fig. 9: Blocking ratios when disaster happens at node 7 in NSF network.

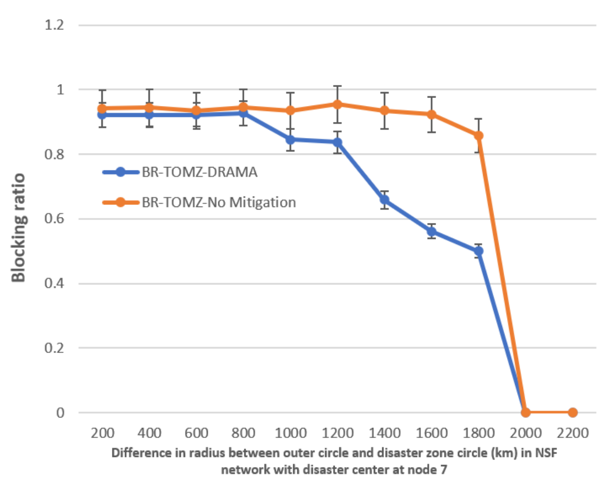


Fig. 10: Blocking ratios when disaster happens at node 7 in NSF network.

V. Conclusion

Disaster management is an important issue in EONs. In this work, we proposed the concept of a mitigation zone to assist disaster recovery; service outside the mitigation zone is not degraded, while the service inside the mitigation zone may be degraded in an effort to improve recovery. We formulated a disaster recovery problem and proposed a heuristic algorithm called DRAMA. Results indicate that the mitigation zone can help reduce the penalty of disaster recovery.

Acknowledgement

This work was supported in part by NSF grant CNS-1818858.

References

[1] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies," *IEEE communications magazine*, vol. 47, no. 11, pp. 66–73, 2009.

[2] Y. Hirota, H. Tode, and K. Murakami, "Multi-fiber based dynamic spectrum resource allocation for multi-domain elastic optical networks," in *2013 18th OptoElectronics and Communications Conference held jointly with 2013 International Conference on Photonics in Switching (OECC/PS)*, June 2013, pp. 1–2.

[3] J. Wu, M. Xu, S. Subramaniam, and H. Hasegawa, "Routing, fiber, band, and spectrum assignment (rfbsa) for multi-granular elastic optical networks," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.

[4] ——, "Joint banding-node placement and resource allocation for multi-granular elastic optical networks," in *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, Dec 2017, pp. 1–6.

[5] G. Shen, H. Guo, and S. K. Bose, "Survivable elastic optical networks: survey and perspective," *Photonic Network Communications*, vol. 31, no. 1, pp. 71–87, 2016.

[6] H. M. Oliveira and N. L. da Fonseca, "Algorithm for fipp p-cycle path protection in flexgrid networks," in *2014 IEEE Global Communications Conference*. IEEE, 2014, pp. 1278–1283.

[7] C. Wang, G. Shen, and S. K. Bose, "Distance adaptive dynamic routing and spectrum allocation in elastic optical networks with shared backup path protection," *Journal of Lightwave Technology*, vol. 33, no. 14, pp. 2955–2964, 2015.

[8] R. Zou and S. Subramaniam, "Novel p-cycle selection algorithms for elastic optical networks," in *ONDM 2019 - 23rd International Conference on Optical Network Design and Modeling (ONDM 2019)*, Athens, Greece, may 2019.

[9] H. H. Rujia Zou, Suresh Subramaniam and M. Jinno, "P-cycle design for translucent elastic optical networks," in *2019 IEEE Global Communications Conference*, Waikoloa, USA, dec 2019.

[10] R. Zou, H. Hasegawa, M. Jinno, and S. Subramaniam, "Link-protection and fipp p-cycle designs in translucent elastic optical networks," *Journal of Optical Communications and Networking*, vol. 12, no. 7, pp. 163–176, 2020.

[11] S. Li, R. Gu, G. Zhang, Y. Wang, Y. Wang, and Y. Ji, "Order aware service recovery algorithm in elastic optical network with multiple failures," in *2019 International Conference on Networking and Network Applications (NaNA)*. IEEE, 2019, pp. 135–141.

[12] M. W. Ashraf, S. M. Idrus, R. A. Butt, and F. Iqbal, "Post-disaster least loaded lightpath routing in elastic optical networks," *International Journal of Communication Systems*, vol. 32, no. 8, p. e3920, 2019.

[13] H. Yu and C. Yang, "Partial network recovery to maximize traffic demand," *IEEE communications letters*, vol. 15, no. 12, pp. 1388–1390, 2011.

[14] S. Ferdousi, F. Dikbiyik, M. Tornatore, and B. Mukherjee, "Joint progressive recovery of optical network and datacenters after large-scale disasters," in *2017 Optical Fiber Communications Conference and Exhibition (OFC)*. IEEE, 2017, pp. 1–3.