Multi-repairmen problem for disaster recovery of optical networks

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ABSTRACT

Survivability of optical networks is a growing concern because of strong reliance on the internet to accomplish our daily activities. This high reliance makes telecommunication infrastructure vital to our daily life. Accordingly, when large network failures occur due to a disaster, the whole community (network operator and end users) incur grave consequences. Hence, the quest of telecommunication infrastructures recovery after a disaster is indispensable. Even though some research focus on how to avoid such large scale failures, sometimes it is inevitable and fast recovery is required. In this study, we investigate the problem of multi-repairmen scheduling and assignment for disaster recovery of optical networks. Given a set of repairmen to repair a set of failures in the network in the aftermath of a disaster, the goal is to allocate each repairman to a set of failures in an intelligent manner such that we maximize recovered capacity as soon as possible for each recovery schedule thereby recovering more capacity as early as possible. We address the problem by proposing a Multi-Repairmen Disaster Recovery Algorithm (MRDRA) that provides intelligent recovery schedule for a given set of failures and repairmen. Finally, we present numerical results that show the potential merits of our study by considering a 24-node US nation-wide topology and an 11-node COST239 European topology. Numerical results show that our approach can recover more capacity compared to classical scheduling significantly.

Keywords: Multi-Repairmen, Disaster Recovery, Optical Network

Optik ağların afet sonrası onarımı için çoklu tamirci problemi

ÖZ

Günlük aktivitelerimizi sağlamak için internete olan bağlılığımız her geçen gün artmakta ve internetin omurgasını oluşturan optik ağların dayanıklılığı da bu nedenle büyüyen bir endişeye dönüşmektedir. Bu nedenle, afet kaynaklı geniş çaplı ağ arızaları oluştuğunda, toplum (ağ operatörleri ve son kullanıcılar) ağır sonuçlarla karşı karşıya kalmaktadırlar. Bundan dolayı afet sonrası haberleşme altyapısının ivedilikle onarılması için arayışlar kaçınılmazdır. Her ne kadar bazı araştırmalar geniş çaplı afetlerden optik bağlantıları sakınma üzerine odaklanmış olsa da bazen arızaların oluşması kaçınılmazdır ve servislerin çalışabilir hale gelmesi için hızlı bir onarma gereklidir. Bu çalışmada afet sonrası onarım için çoklu tamirci zamanlaması ve ataması problemi incelenmiştir. Afet sonrası oluşan bir arızalar kümesi ve ağ tamiri üzerine uzmanlaşmış bir tamirci kümesi verildiği düşünüldüğünde, bu çalışmanın amacı her bir tamirciyi arızalara uygun bir şekilde atamaktır. Öyle ki onarım sürecinde mümkün olan en kısa sürede mümkün olan en büyük miktardaki kapasite onarılmış olsun. Bu problemin çözümü için, verilen bir arızalar ve tamirciler kümesi için akıllı bir şekilde kurtarma planı oluşturan bir Çoklu Tamirci Afet Onarma Algoritması önerdik. Çalışmanın sonunda önerilen algoritmanın potansiyel faydaları, 24 düğümlü ABD ulusal ağı ve 11 düğümlü COST239 Avrupa ağı topolojileri için elde edilen sayısal sonuçlarla gösterildi. Sayısal sonuçlar, geliştirilen algoritmanın klasik onarım yaklaşımları ile kıyaslandığında daha kısa sürede daha çok kapasite onardığını göstermiştir.

Anahtar Kelimeler: Çoklu tamirci problemi, afet sonrası onarım, optik ağlar

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1. INTRODUCTION

Network survivability is a growing concern in telecommunication industry nowadays due to strong reliability on communication services to accomplish our daily activities. When there is telecommunication infrastructure failure the whole community suffers a grave consequence in terms of monetary and social aspects [1] [2] [3] [4]. In principal, survivability of a network is an augmentation of fault tolerance. Authors in [5] define survivability as the ability of a network system to accomplish its mission on time in the presence of attacks, such as natural disasters or man-made attacks. Thus, the problem of network survivability can be considered as provisioning network services regardless of the constraints facing network infrastructures. Generally, it involves mechanisms that ensure fault tolerance and fault recovery of a network.

Terrestrial optical networks are susceptible to failures associated with human activities or natural disasters such as earthquakes, hurricanes, etc. Failures caused by natural disasters usually prompt monumental impact to network operators and network end users due to huge bandwidth loss and long recovery time [2]. Terrestrial optical networks are affected frequently by link failures prompted by human activities thereby causing cable cuts [6]. Large-scale natural disasters also affect terrestrial optical networks [6] - [7]. The problem of multi-link failure (as in a post-disaster scenario) recovery as well as relocation has been investigated in [8] [9] [10]. In order to mitigate network failures prompted by disasters some telecommunication companies have established network emergency management unit that plans and responds to network failures. For example, in 2001, AT&T Company established Network Disaster Recovery (NDR) program aiming at responding to network failures prompted by disasters [11].

Recovery after a disaster should consider not only network restoration through re-provisioning, but also repair activities executed by the repair crew. Even though re-provisioning may restore some of the connections between nodes that are not in disaster zones, the survived network resources may not be sufficient to carry all the connections that need to be restored. Besides, if the source or destination node of a connection is in a disaster area, this connection cannot be restored by re-provisioning. Repair of network resources is a complicated process when the available repair resources, e.g., number of repairmen, is limited. The problem involves quantitative limitations such as, at a given time, number of available repairmen, number of available repair equipments, number of available vehicles for transportation, the availability of fuel to operate such vehicles, the availability of roads, the reliability of

structures to conduct repair activities, etc. It also involves qualitative limitations such as physical and mental conditions of repair crew, the management and coordination of repair activities, interdependency to other physical and/or management systems, etc. In this work, we only focus on number of available repairmen (that dynamically changes in time) and type of failure (e.g., the number of repairmen to recover that failure, time to repair, etc.). Surely, the other aspects should be also taken into consideration; however, this work can serve as a preliminary work to conduct further research in that direction. Note that even considering only a few aspects of the problem, the solution is not straightforward and requires an extensive work.

Some studies focus on stage-by-stage progressive network recovery on optical networks [12] [13]. The approaches proposed in [12] [13]aims to determine the network equipments to repair at each stage to maximize the recovered traffic at early stages. Another work [14] also focuses on network recovery where they propose a scheme that maximizes traffic during the recovery. However, these work assume that the required repair resources for a failure are available when needed, an assumption that is not practical in real life scenarios.

C. Ma et al. focus on multi-repairmen problem in [15] and [16] for restoration of virtual networks. They consider that the problem is static such that number of failures and number of repairmen do not change during recovery phases. However, after a disaster, there are usually correlated failures (e.g., aftershocks) and new failures may arrive. The size of repair crew may also change. It may decrease due to injuries, sickness, or stress (due to relatives and friends lost because of disaster) or it may increase due to support from other branches. Thus, the problem of assigning available repairmen to current failures is a dynamic problem. In this study, we investigated this problem and provide a heuristic, Multi-Repairmen Disaster RecoveryAlgorithm (MRDRA), which maximizes the recovered traffic as early as possible. The proposed solution is designed to be applied whenever recovery state changes, i.e., a failure is repaired or a new failure occurs.

2. PROBLEM DESCRIPTION

The general flowchart of our proposed solution is shown in Fig. 1. After a disaster, if there is sufficient number of repairmen to cover all the failures, then recovery is completed after all the failures are repaired. However, in practice, the number of repairmen may not be sufficient and a subset of the failures should be recovered first. In this case, the determination of failures that will be repaired depends on the benefit from the repair (how

much capacity, i.e., bandwidth, will be recovered after the repair of each failure), the travel time to the failure location, and the repair time. The goal should be recovered as much bandwidth as possible and as early as possible.

Our approach is subject to following assumptions:

- We consider that the number of repairmen may change in time. Some have to take breaks, some repairmen's shifts may over, some may not be available due to sickness, injury, loss of a relative or a friend. Thus, every time that a recovery decision is made, the number of available repairmen is re-evaluated.
- There are no flaws and setbacks on coordination and management of recovery activities.
- The network recovery activities are independent from structural recovery and search and rescue operations.
- There are always vehicles ready to transport repair crew to relevant failure locations.
- The repair resources required are always available at the hands of repair crew.

The repairmen assignment problem can be reduced to Binary (0/1) Knapsack Problem (BKP) which is an NP-Hard problem. BKP is applicable in solving dynamic programming problems [17] [18] [19]. BKP defines which items to put in a backpack among an item set to increase the value inside the backpack. Thus given a set of items, each having weight and value; and the capacity of knapsack, the problem can beformulated as:

$$\max \sum_{i=1}^{n} v_i c_i \qquad (1)$$

Subject to:

$$\sum_{i=1}^{n} w_i c_i \leq \omega \qquad (2)$$

$$c_i \in \{0, 1\} \qquad (3)$$

Whereby, c_i indicates whether item i is included in the knapsack or not ($c_i = 1$ if it is included and equal to zero otherwise). We modify BKP to address our problem by considering a set of network failures after a disaster and each failure requires a certain amount of repairmen for repair. At a given time, we have set of failures (the items that will be put into the knapsack) with the benefit to be gained after their repair (the value of each item), the repairmen required for each failure (the weight of each
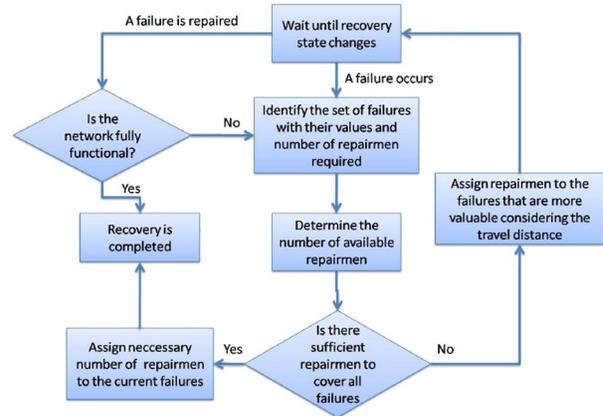

Figure 1. Flowchart of Multi-Repairmen Disaster Recovery Algorithm (MRDRA).

item), and the total number of available repairmen at that time (the capacity of knapsack).

Note that failures are heterogeneous. Some failures (e.g., transponder failures) can be fixed in minutes with a few (or even one) repairmen, while some others (e.g., fiber cuts) may take hours and a significant number of repairmen. The repair of a failure may depend on other failures as well. For instance, to recover the bandwidth of a fiber link all related failures, such as amplifier failures and/or fiber cuts on that link, should be repaired. If we consider sole benefit from the repair of an amplifier on a fiber where there is also a fiber cut on that fiber, then the benefit would be zero, because the repair of amplifier alone cannot provide connectivity on that cable. Thus, we also consider the dependencies between failures and consider failure sets to be repaired instead of single failures.

The gain from a repair depends not only the amount of bandwidth that can be recovered, but also how quickly it can be recovered. Hence, we define the benefit from a repair as a division of bandwidth recovered to time of recovery (sum of travel time and repair time).

We propose a Multi-Repairmen Disaster Recovery Algorithm (MRDRA) where the flow chart is shown in Fig. 1 that solves the problem considering a disaster, multiple links, amplifiers and transponders failures, as well as number of available repairmen. In this context, a network is thought of a system of nodes connected by links of fiber optics. Amplifiers are included in the network for amplification of signal after a certain propagation distance (e.g., 100 km). Moreover, there are transponders for transmission and reception of optical signal at each node.

3. FAILURE IDENTIFICATION AND REPAIRMEN ASSIGNMENT

Given:

- $G(N, E, A)$: network topology where N is a set of nodes, E is a set of edges, and A is as set of amplifiers in a network.
- ϑ: set of dependent-failure sets in a network in the aftermath of a disaster at a given time. Each element $f \in \vartheta$ includes the set of failures with their coordinates, the capacity recovered after the repair of failure set, and number of repairmen required to repair all the failures in f.
- C_f : capacity recovered after the repair of failure set $f \in \vartheta$.
- R_f: repair time of failure set $f \in \vartheta$.
- B_f: benefit from repair of failure set $f \in \vartheta$.
- $m[i; \eta]$: maximum benefit that can be attained with number of repairmen required less than or equal to η using failure sets up to i.
- μ: set of available repairmen at a given time.
- η_f: minimum number repairmen required for failure set $f \in \vartheta$.

In principle, the problem is divided into two sub-problems viz: (i) Identification of failures to be recovered at a given time and (ii) repairmen assignment to each failure such that the benefit is maximized. The solution for the first sub-problem is given in Alg. 1. Here, we look at the failures from the repair of each link. Because, some bandwidth is recovered if and only if the fiber link is repaired. The repair of fiber links consists of repairing a set of dependent failures. First, we need to determine capacity recovered if we repair each link's failure set and number of repairmen required for this failure set. Calculation of C_f is straightforward and depends on how many transponders are in the failure set. In current networks, one transponder at each end node will give a bandwidth of a wavelength capacity. The determination of η_f depends on the repair type. For instance, repair of a transponder can be done by one repairman, while repair of fiber cable break requires more repairmen. Depending on the skills of the repairmen and repair policy of network operator, this number can be considered fixed for each type of failure.

After the identification of failure sets, we need to determine the benefit that can be achieved through repair of each failure set. After this point, the problem becomes similar to BKP (the number of repairmen required is the weight and benefit is the value for each failure set, while number of available repairmen is the capacity of knapsack). There is a pseudo-polynomial time algorithm using dynamic programming [19] that we modify it for our problem as shown in Alg. 2.

Algorithm 1: Identification of failures to be repaired[2]

for *each link in network G(N, E, A)* **do**

    Check if link, amplifiers and transponders are functional.

    if *any equipment on the link is not functional* **then**

        Determine the failure set *f*.

        Get coordinate of each failure in *f*.

        Calculate C_f and η_f.

        Add *f* to ϑ.

    end if

end for

Since the number of repairmen required for each failure set (η_f) and the total number of available repairmen at a given time (μ) are positive integer values, we can define $m[i; \eta]$ (the maximum benefit that can be attained with number of repairmen less than or equal to η using failure sets up to i (first i failure sets)) recursively as follows:

- $m[0; \eta] = 0$
- $m[1; \eta] = m[0; \eta]$ if $\eta_1 > \eta$ (the new failure set is more than the current repairmen limit), else
  $m[1; \eta] = \max(m[0; \eta], m[0; \eta - \eta_1] + B_1)$
- .....
- $m[i; \eta] = m[i - 1; \eta]$ if $\eta_i > \eta$,   else
  $m[i; \eta] = \max(m[i - 1; \eta], m[i - 1; \eta - \eta_i] + B_i)$

Then the solution is obtained by computing $m[|\vartheta|; \mu]$ from the outputs of Alg. 2. The calculations of R_f and B_f in Alg. 2 are straightforward. R_f (repair time of failure set) is equal to sum of time to required of repairmen to reach the failure locations and time to required to repair. Estimated times to repair values of different equipments are usually known and are publicly available. The calculation of B_f is division of capacity recovered to repair time (C_f / B_f).

Note that we apply Alg. 1 and Alg. 2 consecutively whenever the recovery state changes, i.e., a new failure occurs or a failure is repaired, as shown in Fig. 1.

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[2] Our focus on this work is failures of fiber optical cables, amplifiers, and transponders.

Algorithm 2: Repairmen Assignment

for *each f in ϑ* **do**

    Calculate the repair time of failure set $f(R_f)$ based on current locations of available repairmen.

    Calculate the benefit (capacity that can be recovered times over the repair time) of failure set f (B_f).

end for

for *j from 0 to $|\mu|$* **do**

    $m[0; j]$: 0.

end for

for *i from 1 to $|\vartheta|$* **do**

    for *j from 0 to $|\mu|$* **do**

        if $w[i-1] > j$ **then**

            $m[i; j] \coloneqq m[i-1, j]$

        else

            $m[i; j] \coloneqq \max(m[i-1, j], m[i-1, j-\eta_i] + B_i)$

        end if

    end for

end for

Figure 2. A 24-node US nation-wide topology

Figure 3. 11-node COST239 European topology

4. ILLUSTRATIVE NUMERICAL EXAMPLES

We conducted numerical examples on two physical network topologies namely 24-node US topology and 11-node COST239 Europe topology shown in Fig. 2 and 3, respectively. We assume that a link is operational only if all amplifiers on it are operational and there is at least one transponder working on each end point of the link. Moreover, if all transponders are not functional, then the link is not fully functional. The speed of each repairman when moving to the repair point is 50 km/hr.The number of transponders is 16, number of repairmen is 30, capacity of each transponder is 10 Gbps and the interval between amplifiers is 100 km. We compare our approach with a classical approach where repairmen are assigned to the closest failure points to minimize recovery time. We report the amount of recovered capacity for each hour.

We run simulation for 50 scenarios and for each physical network topology, whereby in each scenario we generate a random disaster that cause some equipment to fail with some probability that follows Gaussian probability depending on distance from the disaster's epicenter [20]. Examples are conducted on a computer with an Intel i3 2.4 GHZ CPU, 4 GB DDR3 RAM, and 64 bit Microsoft Windows 10 operating system. Below, we present numerical results for each physical network that shows potential benefits of our study.
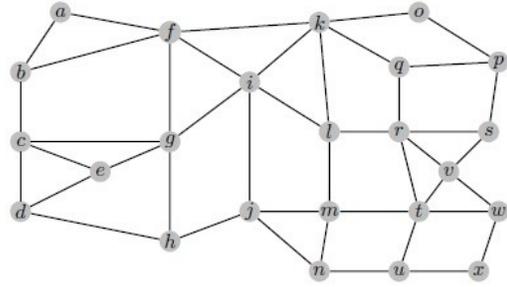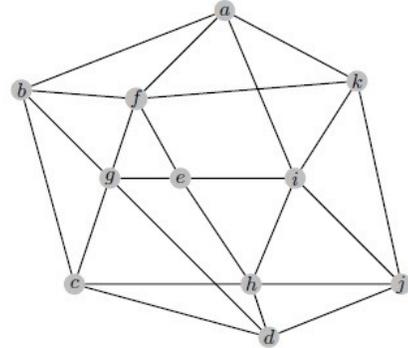
Figure 4 presents numerical results for 24-node US mesh network topology. Since our approach aims to maximize recovered capacity as early as possible, the recovered capacity reaches 2 TB in 10 hours, while the same amount of capacity can only be recovered after 14 hours with classical approach. Similarly, 4 TB capacity is recovered in 18 hours with our approach that is 5 hours earlier than classical approach. After 25 hours, our approach recovers 6 TB capacity, while classical recovers 5TB.
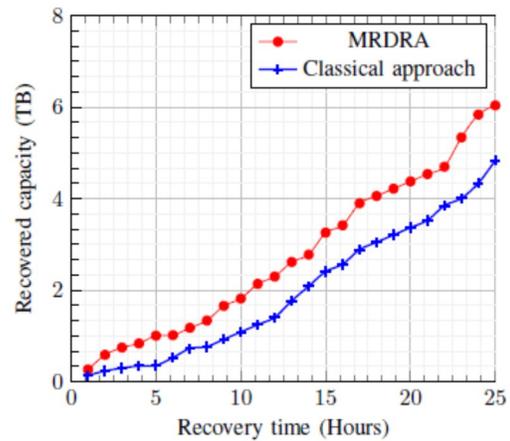

Figure 4. Cumulative recovered capacity per hour for 24-node US mesh network.

Figure 5 reports the cumulative recovered capacity for COST239 topology. We see a similar trend to Fig. 4. In early hours (the first3 hours), it seems that both approaches shows very close results to each other, but then our approach starts to recover faster than the classical approach. For instance, our approach recovers 2 TB in 10 hours and 4 TB in 20 hours, while classical approaches recovers same amounts of capacities in 14 and 23 hours respectively. At the end of 25 hours, while approach recovers 5.8 TB capacity, classical approach recovers only 4.8 TB.
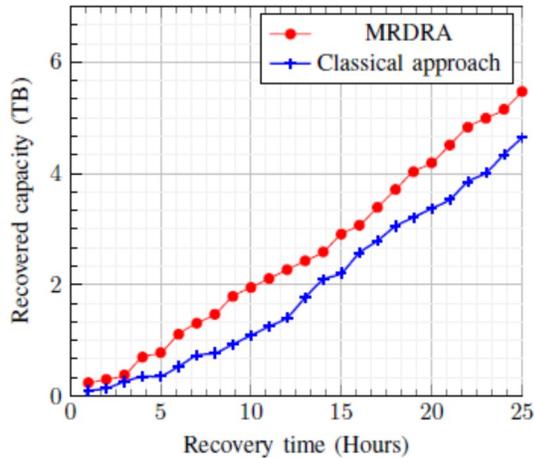

Figure 5. Cumulative recovered capacity per hour for 11-node COST239 network.

5. DISCUSSION

In this study, we focus on the network recovery problem by considering the changes in number of repairmen in time, new failure arrivals after a disaster, interdependency between failures. However, the nature of the problem is more complicated and requires interdisciplinary work with civil engineers, management information system experts, behavioral scientists, etc. Taking this work as a baseline approach, a further research can be conducted with researchers from different disciplines.

6. CONCLUSION

In this study, we investigated the problem of optical network recovery wherein the focus is increasing recovered capacity while minimizing recovery time following network failures associated with disasters. We considered repairing multiple failures in a network such as amplifier, link, and transponder failures given a limited set of repairmen to be involved in reparation activity. We proposed Multi-Repairmen Disaster RecoveryAlgorithm (MRDRA) that provides recovery schedule such that we can maximize recovered capacity

at a given time during recovery. The numerical examples showed for 24-node US and 11-node COST239 Europe topologies that, with an intelligent recovery plan that considers dependency between failures, capacity recovered, and time of recovery (travel time plus repair time), would provide larger capacity at a given time during the recovery compared to a blind approach that only minimizes recovery time.

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