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FRADIR-II: An Improved Framework for Disaster Resilience*

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Abstract

In this paper, we present a framework for disaster resilience, called FRADIR-II, which improves the performance of its previous counterpart. In the novel framework, two different failure models are jointly considered: independent random failures and regional failures that may be used to model the effect of disasters. First, we design an infrastructure against random failures, termed as the spine, which guarantees a certain availability to the working paths. Second, in order to prepare this infrastructure against disasters, we introduce a probabilistic regional failure model, where a modified Euclidean distance of an edge to the epicenter of a disaster is used. The proposed function jointly takes into account the physical length of the edges and their availability, so that a higher/lower availability is reflected in a higher/lower distance from the epicenter. This novel availability-aware disaster failure model generates a failure list which is deemed to be more realistic than previous approaches. Next, a heuristic for link upgrade attempting at the reduction of the likelihood of regional failures disconnecting the network is proposed. Finally, a generalized dedicated protection algorithm is used to route the connection requests, providing protection against the obtained failure list. The experimental results show that FRADIR-II is able to provide disaster resilience even in critical infrastructures.

Keywords: disaster resilience, probabilistic failure, regional failure, spine, general dedicated protection

1 Introduction

Communications services are ubiquitous in today's society. Many mission critical services depend on the continuity of network connections, usually quantified as Quality of Resilience (QoR) [7]. Examples of mission critical services are telesurgery or stock market, as both require very high reliability and availability, which are determined by the underlying network infrastructure, proper failure modeling and by the used routing schemes (i.e., protection mechanism). However, networks are usually designed to consider only single link failure [13] or dual failure scenarios [12], which is clearly not sufficient to satisfy these requirements.

Significant network outages, where telecommunication equipment in a given area becomes non-operational, can be classified as disasters. These can be due to natural events (earthquakes, hurricanes, tsunamis, tornadoes, etc), human error (technical error that may result in a cascading failure) or malicious attacks (hacking and/or using weapons of mass destruction). These failures can be modeled as *Shared Risk Link Groups* (SRLGs), where an SRLG consists of a set of links which are considered to share a common resource (e.g., links sharing a fiber, a cable or a duct). Communication service providers must have contingency plans and designed response actions to protect these SRLGs in the case of disasters (natural or man-made). Hence, approaches either to mitigate the effect of disasters, or to increase the disaster resilience of a communications transport network have recently raised significant interest [10, 14, 21].

Geo-diverse routing can be used to increase network survivability to such failures, where spatial separation between disjoint paths is ensured [4, 6, 8]. However, for an improved performance disaster failures have to be modeled, which is difficult from a probabilistic point of view [24], and it also has conflicting objectives: simplicity and accuracy[1]. Natural disasters can be modeled by *regional failures* which correspond to the joint failure of nodes/links located in the considered affected geographic area [15, 16, 23] – this approach seeks to be a compromise between accuracy and state space explosion. Besides the physical locations of the links, the FRAmework for DIsaster Resilience [18] (*FRADIR*) considers their availability as well, resulting in more realistic regional failures.

In the current paper we further improve the FRADIR framework by introducing a novel regional failure model, where a modified Euclidean distance of an edge to the epicenter of a disaster is used to incorporate both the link lengths and availabilities into the model. Furthermore, we provide a heuristic algorithm for upgrading links in order to minimize the probability of failures disconnecting the network.

The rest of the paper is organized as follows. Section 2 presents a brief overview of the original FRADIR and related work, and in Section 3 we introduce our improved version of this framework, with a more realistic failure modeling. Experimental results are presented in Section 4 to illustrate the advantages of FRADIR-II, and some final remarks are given in Section 5.

[1]The more is known about the geographic link positions and locations of natural disasters, the better one can estimate the probability of simultaneous failure of a given link set. However, sophisticated modeling is required.

2 Related Work

2.1 Resilience and survivability

To be resilient against independent failures, network availability and reliability can be improved by using *network topology design* tools [9, 17, 19, 22]. Alternatively, one can define, at the physical layer, a high availability sub-graph, designated the *spine* in [25]. This approach allows to offer not only high available services (combined with additional protection schemes) but also much more differentiated QoR classes as shown in [2], making this strategy especially suited to support critical services. A similar approach, but that does not consider availability explicitly, is proposed in [26], where the authors consider shielding some links to enhance network robustness.

In addition or as an alternative *survivable routing schemes* can be used to improve the resilience of the connections [20]. General Dedicated Protection (GDP) is a family of survivable routing algorithms that ensure instantaneous failure recovery against any survivable failure pattern (i.e., an SRLG list) [5]. The GDP calculates a minimum cost acyclic graph, for a given source to destination, that ensures connectivity in all considered failure scenarios (i.e., for the given SRLG list).

2.2 Brief Overview of FRADIR

In FRADIR [18] it was shown that combining network design, failure modeling and survivable routing yields great benefits to improve disaster resilience of mission-critical applications, compared to the methods which only consider one of the methods at a time. Furthermore, FRADIR considers jointly two different failure models, which are usually used separately: independent failures (e.g., cable cuts) and regional failures (i.e., disasters).

In FRADIR we used the spine concept to ensure a given availability for all Working Paths (WP). Identical relative incremental availability values for the links selected to be on the spine were considered, resulting in a new upgraded network. This upgraded (spine enhanced) network was analysed with the help of a new *regional failure modeling* method which already incorporated the link availability values into the model. It was shown that the spine is able to significantly reduce the number of SRLGs, i.e., the number of failure events above a given probability threshold. Finally, based on the generated SRLG list a *survivable routing scheme*, e.g., GDP with routing (GDP-R) [5] or SRLG-disjoint path pair (1+1 protection) was used to improve the resilience of the connections. The experiments

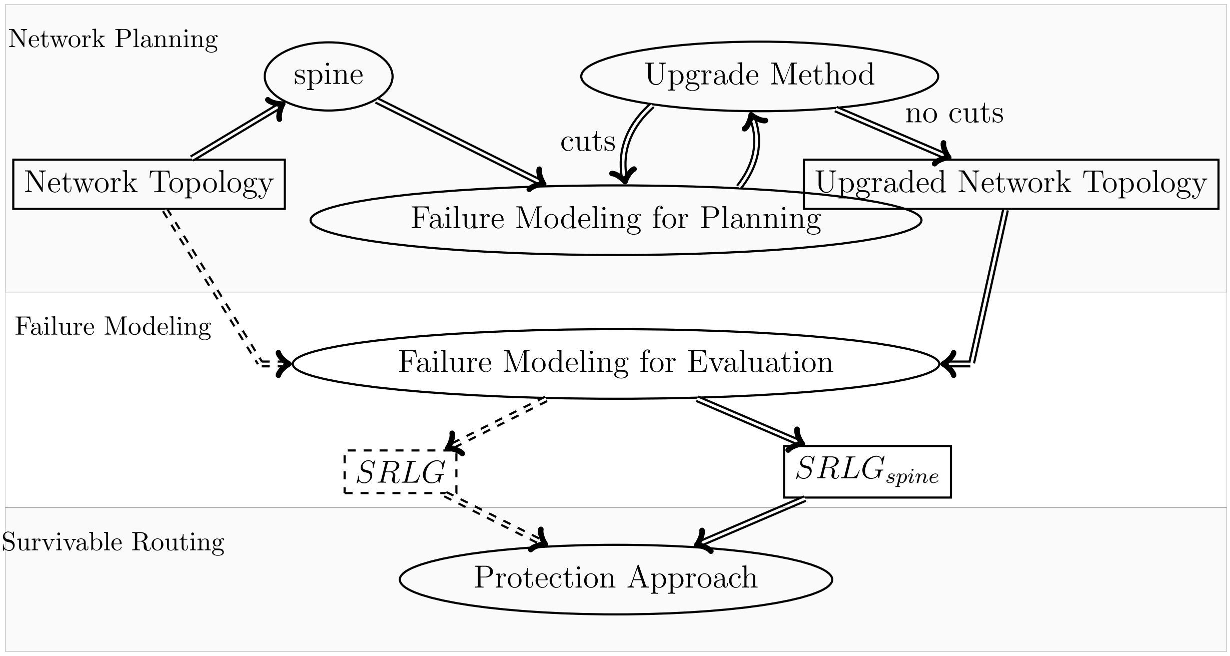

Figure 1: The concept of FRADIR-II. Dashed lines represent the scenario without topology upgrade, while the full lines represent the scenario with the spine concept and algorithm 1 included.

in [18] showed that the GDP-R – which minimizes the total bandwidth cost and provides the optimal solution for non-bifurcated flows – outperforms the 1+1 in each scenario in terms of blocking probability and resource allocation. However, it was highlighted that when considering regional failures the network gets disconnected very often resulting in a non-protectable failure scenario.

Hence, in FRADIR-II besides utilizing a more realistic cost based spine model (Section 3.2) and improving the regional failure modeling technique with a novel availability-based distance function (Section 3.3), we put the emphasis on providing a network design algorithm which is able to identify and prevent the possible network disconnections (Section 3.4).

3 FRADIR-II – Disaster Resilient Transport Networks

Similarly to FRADIR, FRADIR-II combines network planning, failure modeling and survivable routing, shown in Figure 1. In the *network planning layer*, first we design an infrastructure of high availability, which is called the spine. In this work, the availability of the links on the spine is determined seeking to minimize the links upgrade cost [3] –

see Section 3.2 – while satisfying the minimum end-to-end desired availability of the WPs, which include only links on the spine. Note that the constraint that every WP must have a link-disjoint Backup Path (BP) is not enforced here.

The spine calculation model does not take into account regional failures (SRLGs), they are added in the second step (failure modeling for planning). To ensure the network has a very low probability of disconnection under any single regional failure event (when link sets with failing probability over the threshold are considered for an SRLG selection), none of the SRLGs should contain a cutset. Reducing the likelihood of regional failures disconnecting the network is crucial since GDP-R (in the *surviable routing layer*) is able to protect any failure scenario if the network remains connected. Hence, a new upgrade method is considered in the network planning layer (algorithm 1), which seeks to identify links to be further reinforced (which is translated into a higher availability, and thus making them less likely to be part of an SRLG) so that none of the identified SRLGs contain a cutset. This is done iteratively with the help of failure modeling for the planning, as shown in Figure 1.

The availability values of the upgraded network topology can be used in the *failure modeling for evaluation layer*, which provides the final regional failure (SRLG) list for the survivable routing approach. The detailed description of these procedures are given in the next subsections.

3.1 Network Model

Let the network be represented by an undirected graph $G = (V, E, c, a)$ in the plane $\mathbb{R}^2$, where V is the set of nodes representing OXCs (Optical Cross-Connects) and E is the set of undirected edges representing bidirectional fiber connections between the OXCs with the corresponding cost and availability values. Each undirected edge may be represented as a pair of directed links in opposite directions pertaining to a set E_d. The position of each node in the plane is given by coordinates (x, y). Edges are considered as straight line segments (intervals) in $\mathbb{R}^2$ linking their endpoints. For each edge $e \in E$, we define an availability value $a(e) \in [0, 1]$: $a(e) = 1 - \frac{MTTR}{MTBF(e)}$. The mean time to repair a failure is $MTTR = 24$ h and the mean time between failures is $MTBF(e) = \frac{CC*365*24}{\ell(e)}$ [h]. The parameter CC stands for the cable cut metric, considered 450 km. Note that the availability of an edge is a function of the length of the edge, $\ell(e)$ [km]. A cost function $c(e)$ is defined for each edge, corresponding to the cost of allocating a unit of demand (i.e., wavelength) on the given edge e. In this work, the value to be used in GDP-R is $c(e) = 1, \forall e \in E$. Hence, cost efficiency is equivalent to capacity efficiency.

3.2 Spine Design

The high availability structure (i.e., the spine) was obtained using the method described in [3], with some modifications. In this approach, a spine is devised so that a set of edges forming a *spanning tree* is selected and the WPs for all the demands include edges on the spine only. A minimum value for the availability of each WP, $\widehat{a_{wp}}$, is set in advance. The possibility of changing the availability of the edges of the spine is taken into account. In some cases, the availability of an edge may be excessive for achieving the desired availability of the paths, and there may be a downgrade of the availability. In other cases, it may be necessary to upgrade the availability of an edge. This allows for the transfer of some maintenance and repair capabilities between edges, which may be interesting for a company to explore.

Let $a_0(e)$ be the initial availability of edge $e \in E$ and $\bar{a}(e)$ be an upgraded or downgraded availability of the same edge. In [3, Eqs.(3)-(6)], the authors explain how to calculate the upgrade cost (if positive) or a downgrade profit (if negative), considering three different cost functions. We will focus on cost function f_{c3} of [3], i.e., the cost of upgrade (or downgrade) is given by

$$\mathcal{C}(e) = -\ln\left(\frac{1-\bar{a}(e)}{1-a_0(e)}\right)\ell(e) \tag{1}$$

The aim is to find the edges that should form the spine and their final availability values, such that the total cost of upgrade is minimized, while satisfying the established minimum value for the availability of each WP.

In our formulation, we consider 4 different target availability values, i.e., we assume $\bar{a}(e)$ may take one of $K = 4$ possible values $a_k, k = 1, ..., K$ regardless of the initial availability value of each edge $a_0(e)$: $a_1 = 0.999$, $a_2 = 0.9995$, $a_3 = 0.9999$, $a_4 = 0.99995$. We provide some information on the problem formulation so that the text is self-contained. For further details, see [3]. The problem is formulated in terms of directed links $(i, j) \in E_d$. Following the notation in [3], let the binary variables x_{ij} be 1 if link (i, j) is in the spine and 0 otherwise; r_{ij}^k be 1 if the final availability of link (i, j) is $a_0(i, j)$ $(k = 0)$ or a_k, with $k = 1, ..., K$. We redefine $\mathcal{C}_{ij}^k = -\ln\left(\frac{1-a_k}{1-a_0(i,j)}\right)\ell(i, j)$, $k = 1, ..., K$. Obviously, $\mathcal{C}_{ij}^0 = 0$, $\forall(i, j)$.

The spine is obtained by solving a linear problem with objective function $\sum_{(i,j)\in E_d}\sum_{k=1}^{K} r_{ij}^k\mathcal{C}_{ij}^k$ (similarly to [3, Eq.(7)]), subject to constraints [3, Eqs.(8),(10)-(11),(15)-(17),(19),(22),(24)-

(28)]. In our formulation, [3, Eq.(18)] is replaced with $\sum_{k=0}^{K} r_{ij}^k = x_{ij}$, $\forall (i,j) \in E_d, i < j$, which guarantees that only the edges of the spine may have their availability changed. The set of edges of the spine is represented by $\mathcal{S}$. The current availability of edge e will be denoted by $a(e)$.

3.3 Availability-Based Regional Failure Model

Both this paper and [18] modify the model presented in [24] – which generates failing probabilities related to the distances of edges from the epicenter of disaster – to incorporate the spine concept. In [18] the (probability) values assigned to each Probabilistic SRLG (PSRLG) provided by [24] are modified based on the availabilities a of the links in a way that in theoretical extreme cases, the values assigned to some SRLGs could exceed 1. To obtain more realistic failure probabilities, in the current paper, a is incorporated into the failure modeling, fixing this issue along with fulfilling some additional requirements as presented in the following.

As an input to the regional failure model we have graph G (along with link availabilities a), maximal radius of the failures (which are overestimated by circular disks) $R \geq 0$, and a threshold $T \in [0, 1]$. The output of the model is an SRLG list containing all the exclusion-wise maximal SRLGs with probability of failure above T. We emphasize that selecting a high threshold value leads to listing only some trivially probable SRLGs (e.g., non-spine single link failures), while a low T value translates into listing a variety of highly improbable failure scenarios.

In our model, we concentrate on disaster shapes overestimated by circular disks (e.g., earthquakes destroy a circular area). Thus, in order to determine whether a disaster with epicenter p and radius r destroys a link e, the only important measure is the distance $d(e, p)$ of the link from the epicenter. Based on this, in order to incorporate the availability of edges in our model, *we use a modified Euclidean distance function* $\overline{d}$ that in case of a link e with a high availability $a(e)$ pretends that e is more distant to the failure epicenter, while in case of a low availability link pretends the link is closer to the epicenter. More precisely, we require that $\overline{d}$ meets the following conditions in case of failure epicenter p and link e:

(i) $\overline{d}(e, p)$ should be a smooth, strictly monotone increasing function of $a(.)$ in interval $[0, 1)$,

(ii) if $a(e)$ equals a certain fixed value of availability of the links $\mathcal{A}$, $\overline{d}(e,p)$ should be equal to $d(e,p)$,

(iii) if $a(e)$ is almost 1, $\overline{d}(e,p)$ should be almost $+\infty$,

(iv) if $a(e)=0$, $\overline{d}(e,p)$ should be equal to 0.

With this notation, defining the modified distance function as $\overline{d}(e,p) = d(e,p)\dfrac{1-\mathcal{A}}{1-a(e)}$ meets previous conditions (i)-(iii), and is also a good approximation for (iv), because if $a(e) = 0$, $\overline{d}(e,p) = d(e,p)(1-\mathcal{A})$, and $1-\mathcal{A} = 0.001$, which is a small number. The parameter $\mathcal{A}$ could be defined as the average availability of the links, for instance. We assign it a fixed value of 0.999. We emphasize again that using this modification $\overline{d}$ of the Euclidean distance function d in the failure model makes it to reflect also the availabilities of the links besides the nature of the disasters, which results more realistic failure scenarios.

To determine the failure probability $P(S)$ of a link set S, we consider the following. Every disaster has an epicenter $\mathcal{P}$ taking values $p \in \mathbb{R}^2$, with the shape overestimated by a circular disk with radius $\mathcal{R}$ taking values $r \in [0,R]$, where R is the maximum range of disasters we want to protect. We consider both $\mathcal{P}$ and $\mathcal{R}$ as random variables. Let $h(p)$ and $g(r)$ be the density function of the disaster epicenter and the disaster range, respectively.

We say a link e is hit by a disaster with centre point p and radius r if $\overline{d}(e,p) \leq r$.

Let $I_{S,p,r,\overline{d}}$ be the indicator variable which is 1 if the disk with center p and radius r hits all the edges of a set $S \subseteq E$, and 0 otherwise. With this notation, the probability of failing link set S is

$$P(S \text{ is hit}) = \int_{p\in\mathbb{R}^2} \int_{r\in[0,R]} I_{S,p,r,\overline{d}}\, g(r)\mathrm{d}r\, h(p)\mathrm{d}p. \tag{2}$$

A sufficiently fine discretization does not affect the precision of our results. We discretize the problem by defining a sufficiently fine resolution, say 1 km, and place a grid of 1 km $\times$ 1 km squares over the plane to assume that the values of the inner integral (i.e. $\int_{r\in[0,R]} I_{S,p,r,\overline{d}}\, g(r)\mathrm{d}r$) are almost identical for every p inside each grid cell. This way, the whole integration problem translates to a summation. As failure probability defined by Eq. (2) is almost identical to the one used in [24] aside from the augmentation $\overline{d}$ of the Euclidean distance function, detailing of the discretization is omitted here. Besides the discretization, in our simulation we considered both h and g to have a uniform distribution, further simplifying the problem.

We take the list $\mathcal{F}_T$ of SRLGs having a failing probability higher than a threshold T, as these SRLGs are considered to have the highest probability of failing after taking into account the availability values of the edges. Note that a routing resilient for a failure $f \in \mathcal{F}_T$ is resilient for every $f' \subseteq f$ too, thus it is enough to protect the network for the set $\mathcal{M}_T$ of maximal elements of $\mathcal{F}_T$, i.e. $\mathcal{M}_T = \{f \in \mathcal{F} | \nexists f' \in \mathcal{F}_T : f' \supset f\}$. In the viewpoint of the SRLG-based resilient routing, $\mathcal{M}_T$ is a compact representation of $\mathcal{F}_T$.

The previously described procedure to generate $\mathcal{M}_T$ will be denoted by `generateSRLG()`. We argue that including the availability values into the failure model yields more realistic SRLGs, where the failure of the component does not only depend on the geographical distance from the disaster but also on the network component's availability. Furthermore, the availability itself depends on various factors (e.g., number of redundant components, frequency of maintenance, etc.).

3.4 Upgrade Method for Disaster Resilience

In [18] it was highlighted that when considering regional failures the network gets disconnected very often – even with FRADIR presented in [18] – resulting in a non-protectable failure scenario. Thus, besides utilizing a more realistic cost based spine model and improving the failure modeling technique, in FRADIR-II we present a new network planning algorithm (algorithm 1, denoted as Upgrade Method in Figure 1), which focuses exclusively on the regional failures. The objective of the algorithm is to iteratively upgrade the links in such a manner that even after the most probable disaster events (obtained through `generateSRLG()`) the network remains connected, in order to give an opportunity for the survivable routing layer to protect the connection. We consider different target values to which the link availability can be upgraded: $a_1 = 0.999$, $a_2 = 0.9995$, $a_3 = 0.9999$, $a_4 = 0.99995$, $a_5 = 0.99999$ and $a_6 = 0.999995$ ($a_0(e)$ is the initial availability value of the link e before any upgrade). All the links in the upgrade list with availability value a_{k-1} may be upgraded to the next level i.e., to a_k, with $k = 1, ..., 6$.

The main idea of the algorithm is to identify the cutsets $\mathcal{M}_T^*$ in the SRLG list $\mathcal{M}_T$ which disconnect the network. To minimize the number of the links that have to be upgraded (for all disaster events) a set cover problem has to be solved i.e., the selection of the links is based on a set cover problem where the cutsets are covered with the links contained in them. To perform the selection a greedy algorithm (denoted by `greedyMinCover()`) is implemented where in each step we choose the link which covers the most cutsets. This algorithm provides us a polynomial approximation for set covering. The solution is a $H(n)$

Algorithm 1: Link upgrade method to remove cutsets

Input: $G = (V, E, c, a)$, R, T, $\mathcal{S}$: set of edges on the spine
Result: $G = (V, E, c, a')$: graph with improved availability values

1 **begin**
2 $a' \leftarrow a$ *// Initial availabilities*
3 **repeat**
4 $G \leftarrow (V, E, c, a')$
// Calculate SRLGs of G
5 $\mathcal{M}_\mathcal{T} \leftarrow$ `generateSRLG`(G, R, T)
6 $E^* \leftarrow \emptyset$ and SRLG cutset $\mathcal{M}^*_\mathcal{T} \leftarrow \emptyset$
// Iterate over the SRLG list to find the cutsets
7 **for** $f \in \mathcal{M}_\mathcal{T}$ **do**
8 $G^* \leftarrow (V, E \setminus \{f\}, c, a')$
9 **if** G^* *is not connected* **then**
// Add edges of the SRLG
10 $E^* \leftarrow E^* \cup \{f\}$
// Add SRLG to the cutset list
11 $\mathcal{M}^*_\mathcal{T} \leftarrow \mathcal{M}^*_\mathcal{T} \cup f$
// Remove edges off the spine
12 $E^* \leftarrow E^* \cap \mathcal{S}$;
// Minimal cover of SRLGs with edges
13 $E^*_{\min} \leftarrow$`greedyMinCover`$(\mathcal{M}^*_\mathcal{T}, E^*)$
// Upgrade edges
14 **for** $e \in E^*_{\min}$ (or E^*) **do**
15 Let $k : a'(e) = a_{k-1}$, then $a'(e) \leftarrow a_k$
16 **until** $E^* \neq \emptyset$

approximation, where $H(n) = \sum_1^n 1/\eta < \ln(n) + 1$ and n is the number of cutsets. As the output we get a list of links ($E^*_{\min}$ in line 13 of algorithm 1) that need to be upgraded.

The pseudo-code of the upgrading method is described in algorithm 1. The input parameters are the graph as G, the radius R, threshold T and the edges on the spine as set $\mathcal{S}$. The result is the graph with upgraded availability values. The method continues upgrading the links until the graph remains connected in case of every listed failures. The first step (Line 5) is the failure modeling of the network which provides us an SRLG set ($\mathcal{M}_\mathcal{T}$) where every SRLG is a set of edges. Next we define E^*, an edge set which will be upgraded later. We iterate over $\mathcal{M}_\mathcal{T}$ and check the connectivity of the graph after removing the edges of the SRLG. If the obtained graph is not connected, we add the SRLG to $\mathcal{M}^*_\mathcal{T}$ and the edges of the SRLG to E^* (Lines 6-11). In this work, we consider the spine to be a tree, i.e. a connected graph with minimal number of edges. To provide a connected

Table 1: Different set of upgraded edges in algorithm 1.

Line 12 \ Line 13	Execute	Skip
Execute	Minimal cover on spanning tree	All on spanning tree
Skip	Minimal cover	All

solution with minimal cost we will focus on upgrading the edges which are part of the spine – see Line 12. This step can be skipped but greatly reduces the cost of providing connectivity. To upgrade only the most necessary edges a set cover problem is solved (`greedyMinCover()`) on the remaining edges and the cut-SRLGs (Line 13). Of course this step could be skipped too, resulting in another upgrade method. At the last step we iterate through the remaining edge set ($E^*_{\min}$ or E^* if the step on Line 13 is skipped) and upgrade it to the next level (Line 15). Then we restart this procedure until no further edges have to be upgraded. Note that, according to whether we skip or perform Lines 12-13, we get four different sets of edges to be upgraded – see Table 1 for the nomenclature for these sets of edges, to be used in the analysis of results.

The cost of the solution of algorithm 1 is given by adding the cost of upgrading the selected edges using Eq. (1).

4 Experimental Results

Experiments were conducted with the reference networks of Europe (16 nodes, 22 edges, average node degree 2.75) [1] and USA (26 nodes, 42 edges, average node degree 3.23) [1]. Only small networks were considered, as the sophisticated approach for edge upgrade using cost functions is only feasible in small instances [3]. The spine considered for the USA network is a sub-optimal solution of the formulated problem (with $\widehat{a_{wp}} = 0.999$) obtained after a 48h run on a Desktop with an i7-3770 CPU @ 3.40GHz and 16 GB of RAM. Due to lack of space, only the results on the USA network are presented. The results for the Europe network show similar characteristics.

We compare the average capacity allocated per connection and the blocking probability of the protection approaches (1+1 SRLG-disjoint protection and GDP-R) with and without upgraded edges. Traffic demands were generated between all $s-t$ pairs with unit bandwidth requirement. Furthermore, the SRLG number and size (i.e., the average number of links in

Table 2: Experimental results without the upgrade method for disaster resilience ($T = 0.001$).

R (%)	No upgraded availabilities GDP-R		1 + 1		Upgraded availabilities (spine) GDP-R		1 + 1	
	Avg.cap.	Block.	Avg.cap.	Block.	Avg.cap.	Block.	Avg.cap.	Block.
2	5.985	0.000	6.738	0.000	4.480	0.000	5.698	0.000
4	6.460	0.151	6.924	0.151	5.295	0.000	6.295	0.000
6	7.895	0.354	7.943	0.354	5.948	0.000	6.658	0.000
8	8.125	0.631	8.142	0.631	6.767	0.077	7.290	0.077
10	9.788	0.797	9.415	0.837	7.750	0.151	8.062	0.151
12	11.911	0.862	9.250	0.975	8.054	0.151	8.406	0.151
14	16.000	0.991	-	1.000	8.156	0.289	8.333	0.289
16	-	1.000	-	1.000	8.957	0.354	8.084	0.452
18	-	1.000	-	1.000	9.184	0.415	8.214	0.526
20	-	1.000	-	1.000	9.222	0.474	8.585	0.548

one SRLG) are investigated in the context of disasters shaped as a circular disk of radius R (in percentage of the network diameter) and considering a threshold T. The upgrade cost for different sets of upgraded edges is analysed too.

4.1 Performance Analysis of Routing with FRADIR-II

In Table 2 we compare the routing results (GDP-R [5] and ILP formulation of 1+1 SRLG-disjoint [11]) without any upgrade and with the spine in context of the regional failure radius R. The upgrade method in algorithm 1 was not considered. The GDP-R outperforms the 1+1 SRLG-disjoint protection in both aspects (blocking probability and average capacity consumption) – in a few cases $1+1$ uses less capacity but only due to higher blocking. However, we can observe that the blocking probability is extremely high even with the spine. This demonstrates the utmost need for additional upgrade mechanisms, which will be accomplished by means of algorithm 1. Given that GDP-R presents better results, only this approach will be considered in the subsequent experiments.

In Table 3 the results of the GDP-R are displayed when besides the spine the upgrade method for disaster resilience (described in Section 3.4) is utilized. In all the scenarios the GDP-R always finds a solution since if the network remains connected the GDP-R is able to obtain a feasible routing (resulting in 0% blocking probability).

For $R \leq 10(\%)$, the results are the same for all the considered sets of edges, which means that the spine (with the cost of 4254) is sufficient to ensure connectivity even after the regional failure events. The upgrade cost is constant too. Only for $R \geq 12(\%)$ does the upgrade method for disaster resilience has an impact on the results, depending on the set of edges to be upgraded. Since the availability levels are discrete and the upgrade methods are heuristics there can be a fluctuation in the SRLG number and size.

For $R \geq 12(\%)$, we can observe that the SRLG number and the average capacity consumption is the lowest for the "All" set and the highest for either the "Minimal cover" or the "Minimal cover on spanning tree" sets. However, if we take the cost into consideration we see that the cost of upgrading the "All" set is significantly higher than the cost of upgrading the considered alternative sets of edges. This means there is a trade-off between the total upgrade cost and the average capacity consumption of the routing (also quite clear when we compare the results obtained for the upgrade of "All on spanning tree" or the "Minimal cover on spanning tree"). We can either invest in the network upgrade (resulting in a lower routing cost) or keep the network upgrade cost low, resulting in a higher average capacity consumption of the routing (since we have to protect against more complex failure scenarios). The solution obtained after upgrading the set of edges of the "Minimal cover on spanning tree" is the best compromise: for $R \geq 14(\%)$, the cost of upgrade is consistently lower, and in some cases it still outperforms the solution obtained after upgrading the "Minimal cover" set, in terms of SRLG number and average capacity consumption.

4.2 SRLG Analysis

To reveal how the choice of T and R is influencing $|\mathcal{M}_T|$, we computed $|\mathcal{M}_T|$ for a set of thresholds and radii for the USA network (and the Europe network, but results are not displayed here) with the spine. In addition we analyse the average SRLG size. Our findings are depicted on Figure 2 (note the logaalgorithmic-like axis for T). Using the discretization described in sub-section 3.3, we placed a fixed size 400×400 grid over the network and its neighborhood. The grid was placed such that every disaster having a radius of $R \leq 22(\%)$ which hit a nonempty set of links have center points inside the grid (thus are considered in the simulation). We assumed that disasters having their center point in the same grid cell have practically the same effect on the network. Each grid cell had the same possibility to become the center of the next disaster.

The first observation is that a radius $R = 20(\%)$ or larger combined with a threshold $T \leq 0.001$ yields a high number of maximal probable failures. This translates to the fact

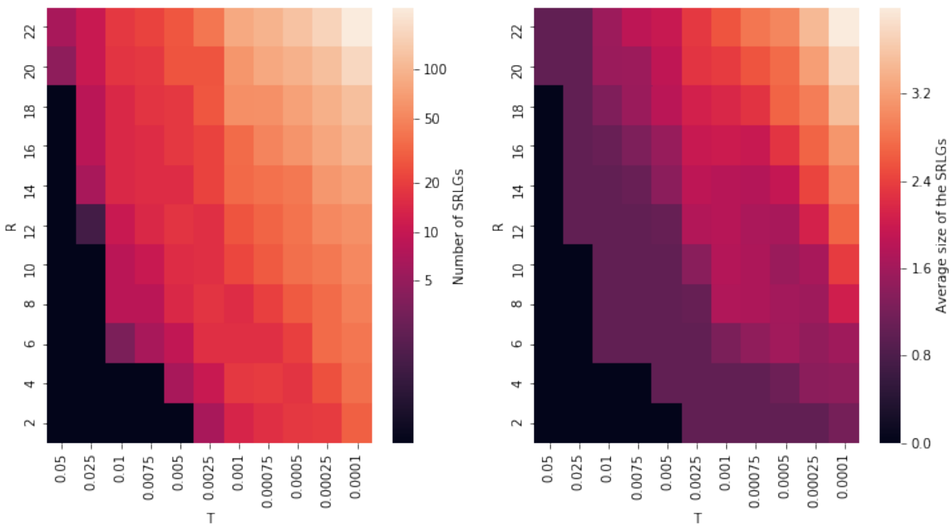

Figure 2: Number of maximal failures $|\mathcal{M}_T|$ in function of T and R with upgraded availabilities due to the spine only.

that a bigger disaster possibly hits a larger number of edges, and the failures above the small threshold cannot be dominated by only a few sets from $\mathcal{M}_T$. Of course, in a non-practical extreme case of R being greater than half of the network diameter it is possible that $\mathcal{M}_T = \{E\}$, meaning $|\mathcal{M}_T| = 1$.

A more interesting observation is that, in our experiments: (i) if $R \in [0, 20](\%)$, $\mathcal{M}_T$ is likely to contain only a handful of most probable SRLGs; (ii) similar $R \cdot T$ value indicates similar cardinality of $\mathcal{M}_T$. Hence, we conclude that, for reasonable disaster sizes $\mathcal{M}_T$ has a manageable size, with its cardinality being comparable with the number of network elements. In addition one can observe that the average size of the SRLG scales with the disaster radius.

5 Conclusions and Future Work

In this work, we proposed an extension to FRADIR [18], a framework to create disaster resilient networks in an efficient manner. The major additions to the previous work were: (i) use of a cost function to select the high availability links on the spine [3]; (ii) identification of relevant SRLGs, representing the considered regional failures, using a new regional failure model, where the availability of each link is translated into information regarding the distance of the link from the epicenter area; (iii) a heuristic to select and upgrade a set of links (with different possibilities) to ensure no SRLG contains a cutset.

Hence, FRADIR-II focuses on maintaining a network connected, which is fully accomplished for the most probable failure scenarios (according to our failure model) we prepared the network for. Some results are presented that illustrate the trade-off between the total upgrade cost and the average capacity consumption of the routing approach.

Some further work is envisaged for creating heuristics for devising the spine, which would allow for experiments with larger networks, where the impact of GDP-R should be more noticeable. Also some improvement of the heuristic for upgrading the links for disaster resilience may be pursued.

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Table 3: GDP-R routing results and upgrade cost for different sets of upgraded edges in algorithm 1 ($T = 0.001$).

R (%)	All SRLG Number	All SRLG Avg.size	All Avg.cap.	All Cost	Minimal cover SRLG Number	Minimal cover SRLG Avg.size	Minimal cover Avg.cap.	Minimal cover Cost
2	13	2.00	4.757	4254	13	2.00	4.757	4254
4	18	2.00	5.406	4254	18	2.00	5.406	4254
6	15	2.67	5.582	4254	15	2.67	5.582	4254
8	15	3.47	5.785	4254	15	3.47	5.785	4254
10	22	3.55	6.735	4254	22	3.55	6.735	4254
12	21	3.24	6.052	5312	26	3.54	6.843	4502
14	30	3.33	7.015	5312	32	3.38	7.892	4727
16	29	3.45	8.163	5312	35	3.71	8.538	4727
18	37	3.68	8.394	5746	51	4.08	9.132	4818
20	41	4.00	8.385	6269	55	4.44	9.178	4928

R (%)	All on spanning tree SRLG Number	All on spanning tree SRLG Avg.size	All on spanning tree Avg.cap.	All on spanning tree Cost	Minimal cover on spanning tree SRLG Number	Minimal cover on spanning tree SRLG Avg.size	Minimal cover on spanning tree Avg.cap.	Minimal cover on spanning tree Cost
2	13	2.00	4.757	4254	13	2.00	4.757	4254
4	18	2.00	5.406	4254	18	2.00	5.406	4254
6	15	2.67	5.582	4254	15	2.67	5.582	4254
8	15	3.47	5.785	4254	15	3.47	5.785	4254
10	22	3.55	6.735	4254	22	3.55	6.735	4254
12	24	3.50	6.446	4714	24	3.50	6.446	4575
14	32	3.50	7.843	4714	34	3.41	8.043	4575
16	30	3.93	8.498	4714	32	3.81	8.643	4575
18	47	4.30	8.951	5015	49	4.20	9.114	4666
20	53	4.68	9.009	5384	56	4.54	9.314	4777