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Improving network availability – A design perspective

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Abstract. The availability of the resources in communication networks is critical, due to the impact that possible disruptions of communication services may have in the society. Therefore providing adequate levels of availability for every demand in a network is of paramount importance. In this work, we focus on the topological structure of a network to select a set of links that provide a high availability path to be used by the different end-to-end demands. This set of links constitutes a high availability structure (the *spine*) and is used as the working path for each demand. The backup path for each demand is edge-disjoint with the corresponding working path. This path pair provides end-to-end protection for critical service demands in the network. An exact formulation of the problem is presented and solved for small instances networks. A heuristic resolution approach with centrality measures is also put forward, with an experimental study comparing the exact and the approximate results.

Keywords: availability, network design, path protection, heuristics, centrality measures

1 Introduction

Communication networks are a critical infrastructure of our society, as is recognized in PDP-21 [1]. Hence improving network resilience and ensuring critical services are maintained in the presence of challenges [2] has been the object of extensive research [3–8].

The concept of Quality of Resilience was introduced in [9] for service differentiation based on its availability and other related parameters. QoR can be used for adequately and quantitatively compare network recovery schemes deployed in a given network architecture [10].

Some works seek to route demands taking into account a desired availability. In [11] the authors propose an algorithm for dynamic traffic, called 3W-availability aware routing (3WAR), assuming historical data allows to know the availability of the links depending on their location, month and time of day. A mathematical model is developed for calculating the availability of a shared-protected connection in [12] and the problem of provisioning connections cost effectively while satisfying the connections' availability requirements is addressed in optical wavelength-division multiplexing (WDM) meshed networks. A theoretical analysis on service availability in elastic optical networks (EONs) is presented in [13]. An availability-aware differentiated protection (ADP) algorithm and a service availability-aware backup reprovisioning strategy are proposed.

The use of different recovery or protection techniques leads to different recovery time and service availability values. However in [14] the values obtained for the availability of three classes (gold, silver and bronze) were not significantly different for gold (with dedicated protection) and silver (with shared protection). Also relevant, was the fact that the gold class availability was significantly below the required value (*i.e.* four to six 9') for mission-critical services.

Improving the availability of selected network elements (nodes and/or links) is a different approach to achieve high availability. In [15] the authors select some links to be shielded, making them resilient to failures. Given a desired end-to-end availability, several variants of a heuristic for selecting links for an availability upgrade is proposed in [16].

In [7, 17, 18] the problem of cost efficiently achieving jointly high levels of availability and service differentiation to traffic flows was addressed. The basic idea is to consider that there is a high availability portion of the network and its elements (nodes and edges) may have an increased availability by using for instance more reliable equipment and/or redundant equipment in parallel. This portion of the network was designated the *spine*. The spine was designed to be a spanning tree at the physical layer, and should be used to route flows of higher QoR classes [7, 17, 18]. The concept of the spine is explored in [18] as a strategy to ensure a high availability to critical services, while providing different levels of resiliency for other (less demanding) services.

In [17] a first approach on how the structural properties of the network topology could be used in a heuristic to select a suitable spine, was presented. In that work the availability of edges was not considered in the spine selection. If the minimum cost spanning tree was not admissible, link pruning was performed until an admissible tree was found (a tree is only admissible if for all working paths in the spine a edge disjoint backup can be found). Hence in [17, 18], after the first tree, no assurance is given with respect to the order of the generated spanning trees for the considered edges weights. In the present work an exact formulation to design the spine according to a specific function is proposed, and several metrics for enumerating the possible spanning trees are evaluated. Note that no cost function is considered in this work, as it is very difficult to obtain realistic cost functions for improving availability. Moreover the objective of the work is to check the adequacy of the proposed metrics, using a small number of spanning trees (generated by non-decreasing cost based on the relevant metric), for obtaining in a reasonable time a spine, with a performance close to the solution of the formulated optimization problem.

The paper is organized as follows: after this introductory section which includes the description of related work, an exact formulation to devise the spine according to a specific function to be optimized is described in section 2. In section 3, we present the used heuristic for the spine calculation and the corresponding paths availabilities. The experimental results are presented in section 4, followed by the conclusions section, where further work is also proposed.

2 Exact formulation

We present an exact formulation for finding an edge-disjoint path pair for each demand in the network, taking into account the availability of each edge. The set of edges used in the working paths (WPs) of all the demands constitutes a spanning tree. For each WP in the spine, an edge-disjoint path will be devised, which will be the backup path (BP) for the corresponding demand.

The devised formulation focuses in finding the spine, *i.e.* in finding the most available WPs, as these are the paths used in regular conditions. Only in the case of failures in any of the components of the WP (a node or an edge) will the BP be used. Therefore, the focus is not in the path pair (WP and BP) and we only require an edge-disjoint path pair to be found for each demand (not necessarily the most available path pair). This is the reason why the objective functions in both exact formulations are related with the availability for the WP only. Moreover, in [18] the maximization of the WP availability was shown to be closely related to the maximization of the path pair availability.

In this section, we begin by defining the notation, followed by the presentation of the exact formulation problems.

2.1 Notation

Sets

- $\mathcal{N}$ is the set of physical nodes in the graph.
- $\mathcal{E}$ is the set of physical undirected edges in the graph.
- $\mathcal{L}$ is the set of directed links in the graph. We may consider an undirected edge with end nodes i and j as a pair of directed and opposite links $(i, j) \in \mathcal{L}$ and $(j, i) \in \mathcal{L}$.
- $\mathcal{F}$ is the set of end-to-end demands or flows. A flow $f \in \mathcal{F}$ between nodes $s \in \mathcal{N}$ and $t \in \mathcal{N}$ may be identified by its source node s and its destination node t, *i.e.* we assume $f \equiv (s, t) \in \mathcal{F}$.

Availability

- $a(l)$ is the availability of edge $l \in \mathcal{E}$. If an edge is identified by the corresponding directed and opposite links $(i, j) \in \mathcal{L}$ and $(j, i) \in \mathcal{L}$, we may identify the availability of each link as a_{ij} and a_{ji}, respectively. In our problem, we will assume the availability of each edge l depends on the length (distance between the end nodes) of each edge, given by $d(l)$. In particular, $a(l) = 0.99987^{d(l)/(250\times1.6093)}$, as in [19].

– $A^{WP}_{(s,t)} = \prod_{l \in WP_{(s,t)}} a(l)$ is the availability of the WP of flow (s,t).

Performance measures related to the availability

– $A^{WP}_{\mathrm{a}} = \frac{1}{|\mathcal{F}|} \sum_{(s,t)\in\mathcal{F}} A^{WP}_{(s,t)}$ is the average value of the availability for the WPs $A^{WP}_{(s,t)}$ of all the flows.
– $A^{WP}_{\mathrm{m}} = \min_{(s,t)\in\mathcal{F}} A^{WP}_{(s,t)}$ is the minimum value of the availability for the WPs $A^{WP}_{(s,t)}$ of all the flows.

Variables to be used in the exact formulation of the problem:

– z_{ij} is 1 if the link (i,j) is in the spine and 0 otherwise.
– x^{st}_{ij} is 1 if the link (i,j) is in the WP of the flow $(s,t) \in \mathcal{F}$ and 0 otherwise.
– y^{st}_{ij} is 1 if the link (i,j) is in the BP of the flow $(s,t) \in \mathcal{F}$ and 0 otherwise.

2.2 Problem 1: Maximization of the sum of availabilities of the WPs of all the flows

In problem 1, the objective function is the maximization of the sum of availabilities of the WPs of all the flows, which is equivalent to the maximization of the average value of the availability for the WPs of all the flows.

The problem is formulated as:

$$\max \sum_{(s,t)\in\mathcal{F}} A^{WP}_{(s,t)} \tag{1}$$

subject to

$$\sum_{(h,j)\in\mathcal{L}} x^{st}_{hj} - \sum_{(i,h)\in\mathcal{L}} x^{st}_{ih} = \begin{cases} 1 & \text{if } h = s \\ -1 & \text{if } h = t \\ 0 & \text{otherwise} \end{cases} \quad \forall h \in \mathcal{N}, (s,t) \in \mathcal{F} \tag{2}$$

$$\sum_{(h,j)\in\mathcal{L}} y^{st}_{hj} - \sum_{(i,h)\in\mathcal{L}} y^{st}_{ih} = \begin{cases} 1 & \text{if } h = s \\ -1 & \text{if } h = t \\ 0 & \text{otherwise} \end{cases} \quad \forall h \in \mathcal{N}, (s,t) \in \mathcal{F} \tag{3}$$

$$x^{st}_{ij} + x^{st}_{ji} \leq 1 \quad \forall (i,j) \in \mathcal{L} \text{ with } i < j, (s,t) \in \mathcal{F} \tag{4}$$

$$y^{st}_{ij} + y^{st}_{ji} \leq 1 \quad \forall (i,j) \in \mathcal{L} \text{ with } i < j, (s,t) \in \mathcal{F} \tag{5}$$

$$\sum_{(h,j)\in\mathcal{L}} x^{st}_{hj} + \sum_{(i,h)\in\mathcal{L}} x^{st}_{ih} \leq 2 \quad \forall h \in \mathcal{N}, (s,t) \in \mathcal{F} \tag{6}$$

$$\sum_{(h,j)\in\mathcal{L}} y^{st}_{hj} + \sum_{(i,h)\in\mathcal{L}} y^{st}_{ih} \leq 2 \quad \forall h \in \mathcal{N}, (s,t) \in \mathcal{F} \tag{7}$$

$$x^{st}_{ij} + y^{st}_{ij} \leq 1 \quad \forall (i,j) \in \mathcal{L}, (s,t) \in \mathcal{F} \tag{8}$$

$$x^{st}_{ij} + y^{st}_{ji} \leq 1 \quad \forall (i,j) \in \mathcal{L}, (s,t) \in \mathcal{F} \tag{9}$$

$$z_{ij} \geq x^{st}_{ij} \quad \forall (i,j) \in \mathcal{L}, (s,t) \in \mathcal{F} \tag{10}$$

$$z_{ij} = z_{ji} \quad \forall (i,j) \in \mathcal{L} \text{ with } i < j \tag{11}$$

$$\sum_{(i,j)\in\mathcal{L}, i<j} z_{ij} \leq |\mathcal{N}| - 1 \tag{12}$$

$$A^{WP}_{(s,t)} = \prod_{(i,j)\in WP_{(s,t)}} a_{ij} \quad \forall (s,t) \in \mathcal{F} \tag{13}$$

$$x^{st}_{ij}, y^{st}_{ij}, z_{ij} \text{ binary} \tag{14}$$

Constraints (2) and (3) represent flow conservation constraints for the WP and the BP, respectively. Constraints (4)-(7) guarantee a loop free routing for the WPs. Constraints (8)-(9) ensure the WP and the BP are link-disjoint.

Constraints (10)-(12) deal with the formation of a minimum spanning tree in the network, which is the spine (composed of all the links in the WPs of all the flows).

Constraint (13), which is used to calculate the availability of the WP of each flow, has to be linearized, which is accomplished by applying logarithms to both sides of the equality. Let $LA^{WP}_{(s,t)} = -\log\left(A^{WP}_{(s,t)}\right)$. Therefore, constraint (13) is replaced by:

$$LA^{WP}_{(s,t)} + \sum_{(i,j)\in\mathcal{L}} x^{st}_{ij} \log\left(a_{ij}\right) = 0, \forall (s,t) \in \mathcal{F} \tag{15}$$

The problem may now be formulated as:

$$\min \sum_{(s,t)\in\mathcal{F}} LA^{WP}_{(s,t)} \tag{16}$$

subject to constraints (2)-(12), (14) and (15).

2.3 Problem 2: Maximization of the minimization of the availability for the WPs of all the flows

The problem formulation is similar to the previous one, except for the objective function, which in this case is $\max \min_{(s,t)\in\mathcal{F}} A^{WP}_{(s,t)}$. Therefore, the problem is formulated as:

$$\max A^{WP} \tag{17}$$

subject to

$$A^{WP} \leq A^{WP}_{(s,t)} \quad \forall (s,t) \in \mathcal{F} \tag{18}$$

$$\text{constraints (2)-(14)}$$

To avoid non-linearities, let $LA^{WP} = -\log\left(A^{WP}\right)$ (non-negative). Constraint (18) is replaced by:

$$LA^{WP} - LA^{WP}_{(s,t)} \geq 0, \forall (s,t) \in \mathcal{F} \tag{19}$$

The problem may now be formulated as:

$$\min LA^{WP} \tag{20}$$

subject to constraints (2)-(12), (14), (15) and (19).

3 Heuristic resolution approach

We present a heuristic for generation of edge-disjoint path pairs for the demands in the network, taking into account the availability of each edge. As already mentioned, the set of edges forming the WPs constitutes a spanning tree and the BP for each demand must be edge-disjoint. Considering the information on the spine and the WP for each node pair, then the performance measures (maximal availability, for instance) may be calculated.

In this section, we explain how the WPs are devised using an algorithm for enumeration of $\mathcal{K}$ trees in non-decreasing order of a cost metric. Different cost metrics are proposed. As for the BP, it suffices to find an edge-disjoint path pair for each demand.

3.1 Generation of WPs

The algorithm in [20] is used to iteratively generate spanning trees by non-decreasing order of a cost metric. Different cost metrics were taken into account. The WP for each demand (source-destination pair) is given by edges in the spanning tree.

In this work, we reserve the term 'edge cost' to the value assigned to each edge during the calculation of spanning trees, and the term 'edge length' to the value assigned to each edge during the calculation of shortest paths. It is not necessarily an actual distance.

The enumeration of shortest paths for each node pair may be necessary for the calculation of some of the cost metrics described in this section. Once a specific cost metric is considered, the enumeration of candidate spines (spanning trees) is performed and only the spanning trees for which an edge-disjoint BP may be found for every node pair are admissible. We discard the spines for which there is at least one demand without an edge-disjoint BP.

Metric {A} In this situation, the final cost of edge l is simply calculated as

$$c^{\{A\}}(l) = -\log(a(l)) \tag{21}$$

which means that the edge cost is directly related to the availability of edge l.

Metrics related to an edge betweenness centrality measure Let the length of an edge l be given by $-\log(a(l))$, where $a(l)$ is the availability of edge l. In this case, enumerating the $\mathcal{K}$ shortest paths between nodes s and t using these lengths corresponds to the enumeration of the $\mathcal{K}$ most available paths between nodes s and t. Therefore, in the path enumeration algorithm, the paths are generated by non-increasing order of availability. Note that different edges may have different lengths and the graph is considered to be weighted.

Given the paths enumerated by non-increasing order of availability, a measure of the betweenness centrality for each edge l, $\mathcal{B}(l)$, may be calculated. The final cost of edge l is calculated as the symmetrical of the centrality measure, with an additional transformation that guarantees that all the costs are positive.

We define 3 different betweenness centrality measures for an edge, which lead to different edge costs.

Metric $\{B\}$ We consider $\mathcal{P}(s,t)$, which is the set of shortest paths between nodes s and t, *i.e.* the set of paths with length equal to the length of the shortest path between nodes s and t. By equal length, we consider a length within a given tolerance ϵ, *i.e.* two paths with length L_1 and L_2 respectively, have equal length if $|L_1 - L_2| \leq \epsilon$. Likewise, the two paths have different length if $|L_1 - L_2| > \epsilon$.

We define $\sigma(s,t) = |\mathcal{P}(s,t)|$ and $\sigma(s,t|l)$ as the number of paths in the set $\mathcal{P}(s,t)$ that include edge l. Given these parameters, then the betweenness centrality for edge l is

$$\mathcal{B}^{\{B\}}(l) = \sum_{(s,t)\in\mathcal{F}} \frac{\sigma(s,t|l)}{\sigma(s,t)} \tag{22}$$

Metric $\{C\}$ For the calculation of this cost, we again start by enumerating the $\mathcal{K}$ shortest paths between nodes s and t using the length of an edge l as $-\log(a(l))$. Let $\mathcal{P}_\delta(s,t)$ be the set of paths between nodes s and t, whose length is not higher than the length of the shortest path (L_0) plus δ (real-valued). The length of the path is related to its availability, *i.e.* the shortest path is the most available. The availability of each edge $l \in \mathcal{L}$, $a(l)$, is related to the edge length $d(l)$ (in km), as explained earlier.

Given the set $\mathcal{P}_\delta(s,t)$, we may define $\sigma_\delta(s,t) = |\mathcal{P}_\delta(s,t)|$ and $\sigma_\delta(s,t|l)$, which is the number of paths in the set $\mathcal{P}_\delta(s,t)$ that include edge l.

A topological structural measure defined by [21] is the δ-betweenness centrality for edge l, given by

$$\mathcal{B}_\delta^{\{C\}}(l) = \sum_{(s,t)\in\mathcal{F}} \frac{\sigma_\delta(s,t|l)}{\sigma_\delta(s,t)} \tag{23}$$

In the performed experiments, the considered value for δ must be tuned for each network.

Metric $\{D\}$ This metric is a variant of the previous one, which allows to decrease the centrality of the edges that are present in (almost) all of the shortest paths for each demand. The idea behind this metric is to decrease the probability of such edges being in the spine, which should allow to find more edge-disjoint BPs. This is especially relevant and noticeable in sparser networks, where the number of possible edge-disjoint path pairs may be critical.

This cost involves a structural measure similar to $\mathcal{B}_\delta^{\{C\}}(l)$. However, rather than considering $\sigma_\delta(s,t|l)$ (the number of paths in the set $\mathcal{P}_\delta(s,t)$ that include edge l), we have to consider two parameters: $\sigma^0(s,t|l)$, which is the number of paths in $\mathcal{P}_\delta(s,t)$ with the same length L_0 as the shortest path and that include edge l; $\sigma_\delta^+(s,t|l)$, which is the number of paths in $\mathcal{P}_\delta(s,t)$ with length L such that $L_0 < L \leq L_0 + \delta$ and that include edge l. Note that $\sigma^0(s,t|l) = \sigma(s,t|l)$ and that $\sigma_\delta(s,t|l) = \sigma^0(s,t|l) + \sigma^+_\delta(s,t|l)$.

We define

$$\mathcal{B}^{\{D\}}_{\delta,\alpha}(l) = \sum_{(s,t)\in\mathcal{F}} \frac{\sigma^0(s,t|l) - \alpha\sigma^+_\delta(s,t|l)}{\sigma_\delta(s,t)} \tag{24}$$

In the performed experiments, the considered values for δ and α must be tuned for each network.

4 Experimental results

Experiments were conducted with different real-world reference networks (geant, polska, newyork[3], germany50) from the SNDlib [22], whose topology features are described in Table 1. The other networks are epan16 [23] and telia-sonera [24]. Given the information on the nodes of each network (that represent cities), it was possible to find out the length of each edge in km.

For the smaller networks, an exact result was obtained by solving problems 1 and 2 with CPLEX 12.5, *i.e.* the spines for which the maximum A^{WP}_{a} and the maximum A^{WP}_{m} were obtained.

Experiments with the different cost metrics were performed and for each experiment, a set of trees was obtained. A maximum number of $|\mathcal{N}| \cdot |\mathcal{E}|$ trees was calculated. The total number of spanning trees that can be found in each network may be calculated, giving the proportion of considered trees $\frac{|\mathcal{N}|\cdot|\mathcal{E}|}{\#\ \mathrm{trees}}$ displayed in Table 1. Note that this proportion is quite different depending on the network.

The $|\mathcal{N}| \cdot |\mathcal{E}|$ calculated trees are the trees which are candidates to becoming spines. As mentioned previously, all the candidate spines (spanning trees) for which an edge-disjoint backup path can be found in the network for each working path in the spine are considered admissible. Given the set of admissible trees obtained in each experiment, information on the tree leading to the best value

[3] Note that in the case of newyork the latitude and longitude are in fact V and H, respectively, of the V&H coordinate system created by AT&T.

Table 1. Network characteristics ($|\mathcal{N}|$, $|\mathcal{E}|$, ν – average node degree, D – diameter, $\overline{d}$ – average link length [km])

Network	$\|\mathcal{N}\|$	$\|\mathcal{E}\|$	ν	$\|\mathcal{N}\| \cdot \|\mathcal{E}\|$	D	$\frac{\|\mathcal{N}\|\cdot\|\mathcal{E}\|}{\#\ \mathrm{trees}}$	$\overline{d}$
polska	12	18	3.00	216	4	4.2%	188.06
epan16	16	23	2.88	368	6	0.84%	325.22
newyork	16	49	6.13	784	3	5.4E-8	105.53
telia-sonera	21	25	2.38	525	9	21.88%	643.80
geant	22	36	3.27	792	5	3.2E-5	1053.17
germany50	50	88	3.52	4400	9	9.6E-17	100.59

of A_{a}^{WP} and on the tree leading to the best value of A_{m}^{WP} is obtained. For the cost metrics $\{C\}$ and $\{D\}$, experiments were run for different values of δ (real-valued); for $\{D\}$, α took values between 0.0 and 1.0, with a step of 0.1.

Note that metric $\{D\}$ makes sense for sparser networks, for which it is difficult to find edge-disjoint BPs for all the flows. In this situation, the centrality measure of metric $\{C\}$ is too demanding and metric $\{D\}$, which tries to decrease the importance of central edges, should perform better. Therefore, metric $\{D\}$ was only used in the polska, epan16 and telia-sonera networks.

The choice of δ depends on the network. We calculated for each demand, the difference in cost of the first and the second shortest paths using the length of an edge l as $-\log(a(l))$. Let $\Delta(s,t)$ be that difference. With this information for all the demands $(s,t) \in \mathcal{F}$, we calculated the values of $\Delta_m = \min_{(s,t)\in\mathcal{F}} \Delta(s,t)$, $\Delta_a = \mathrm{avg}_{(s,t)\in\mathcal{F}}\Delta(s,t)$ and $\Delta_M = \max_{(s,t)\in\mathcal{F}} \Delta(s,t)$. Note that δ and Δ are expressed in terms of the length of edges $-\log(a(l))$ and paths $\sum_{l\in \text{ path}} (-\log(a(l)))$. We will define the corresponding values $\underline{\delta}$ and $\underline{\Delta}$ as distances in km, displayed in Table 2.

In Tables 3-8, information on the values of the performance measures obtained in the experiments considering the exact formulation and the cost metrics is provided. The percentage of discarded trees (*i.e.* spines for which an edge-disjoint path pair could not be found for at least one demand) is also presented. For metrics $\{C\}$ and $\{D\}$, the best results are displayed, with the indication of one value of $\underline{\delta}$ [km] (corresponding to the δ used in the metric) and the range of α (for $\{D\}$ only) for which they were found. For metric $\{D\}$, the percentage of discarded trees is an average of the percentages obtained for the different values of α in the table. Note that different values of δ and α may lead to the same final result.

For the exact formulation problems, we present the optimal value in bold for the corresponding problem (*i.e.* A_{a}^{WP} for problem 1 and A_{m}^{WP} for problem 2). For the heuristics, we present in bold the value of A_{a}^{WP} for one of the trees which led to the best value of that parameter; likewise for A_{m}^{WP}.

In terms of solver execution times, the resolution of problem 1 only takes a few seconds (the maximum is 40s for the geant network) and the resolution of problem 2 can take between a few seconds (eg. the polska and telia-sonera

Table 2. Values related to the difference in distance [km] of the first and the second shortest paths

Network	$\underline{\Delta}_m$	$\underline{\Delta}_a$	$\underline{\Delta}_M$
polska	2.00	175.77	634.39
epan16	2.00	324.93	1420.42
newyork	1.00	36.52	128.12
telia-sonera	2.00	1525.64	5446.51
geant	6.00	312.56	2537.58
germany50	4.02E-11	51.99	479.66

Table 3. Performance results for the polska network

polska	%disc	A_{a}^{WP}	A_{m}^{WP}
Problem 1		**0.9998417777**	0.9996972610
Problem 2		0.9998417777	**0.9996972610**
Cost $\{A\}$	73.15%	**0.9998408580**	0.9996752942
		0.9998379941	**0.9996856314**
Cost $\{B\}$	82.87%	**0.9998417777**	**0.9996972610**
$\{C\}, \underline{\delta} = 185.68$	68.98%	**0.9998417777**	**0.9996972610**
$\{D\}, \underline{\delta} = 1237.84$			
$\alpha = 0.0$	82.87%	**0.9998417777**	0.9996972610
any α	53.54%	0.9998414347	**0.9996972610**

Table 4. Performance results for the epan16 network

epan16	%disc	A_{a}^{WP}	A_{m}^{WP}
Problem 1		**0.9996742529**	0.9992554330
Problem 2		0.9996325619	**0.9992861092**
Cost $\{A\}$	95.92%	**0.9996632651**	0.9991924691
		0.9996505403	**0.9992554330**
Cost $\{B\}$	96.20%	**0.9996632651**	**0.9991924691**
$\{C\}, \underline{\delta} = 804.60$	97.55%	**0.9996734190**	**0.9992554330**
$\{D\}, \underline{\delta} = 3651.64$ $0.1 \leq \alpha \leq 0.2$	72.96%	**0.9996742529**	**0.9992554330**

Table 5. Performance results for the newyork network

newyork	%disc	A_{a}^{WP}	A_{m}^{WP}
Problem 1		**0.9999335993**	0.9998827060
Problem 2		0.9999318975	**0.9998875526**
Cost $\{A\}$	0%	**0.9999294824**	**0.9998675202**
Cost $\{B\}$	0%	**0.9999274629**	0.9998607351
		0.9999268382	**0.9998749515**
$\{C\}, \underline{\delta} = 30.95$	0%	**0.9999323985**	0.9998736591
$\{C\}, \underline{\delta} = 27.85$	0%	0.9999292696	**0.999882706**

Table 6. Performance results for the telia-sonera network

telia-sonera	%disc	A_{a}^{WP}	A_{m}^{WP}
Problem 1		**0.9989526565**	0.9972957260
Problem 2		0.9989101636	**0.9975090909**
Cost $\{A\}$	96.76%	**0.9989526565**	0.9972957260
		0.9989101636	**0.9975090909**
Cost $\{B\}$	100%	No solution with edge-disjoint path pairs in the first $\lvert\mathcal{N}\rvert \cdot \lvert\mathcal{E}\rvert$ trees.	
$\{C\}, \underline{\delta} = 1547.30$	99.81%	**0.9989204946**	0.9970769294
$\{C\}, \underline{\delta} = 1856.76$	99.99%	0.9989169741	**0.9973914445**
$\{D\}, \underline{\delta} = 11140.58$			
$\alpha \geq 0.3$	98.40%	**0.9989526565**	0.9972957260
$\alpha \geq 0.2$	98.92%	0.9989101636	**0.9975090909**

Table 7. Performance results for the geant network

geant	%disc	A_{a}^{WP}	A_{m}^{WP}
Problem 1		**0.9992753570**	0.9969158432
Problem 2		0.9990333026	**0.9970263455**
Cost $\{A\}$	57.95%	**0.9992577379**	0.9969493470
		0.9992218088	**0.9970244124**
Cost $\{B\}$	10.35%	**0.9992719789**	0.9969158432
		0.9992467344	**0.9970263455**
$\{C\}, \underline{\delta} = 340.41$	54.17%	**0.9992753570**	0.9969158432
$\{C\}, \underline{\delta} = 154.73$	34.47%	0.9992454430	**0.9970263455**

Table 8. Performance results for the germany50 network

germany50	%disc	A_{a}^{WP}	A_{m}^{WP}
Problems 1& 2		Due to the network size, the exact algorithm could not be run.	
Cost $\{A\}$	43.45%	**0.9998374813**	0.9996103656
		0.9998371234	**0.9996158569**
Cost $\{B\}$	96.18%	**0.9998373995**	**0.9996313620**
$\{C\}, \underline{\delta} = 123.78$	85.61%	**0.9998419336**	0.9996313620
$\{C\}, \underline{\delta} = 34.04$	95.70%	0.9998308936	**0.9996649570**

networks), a few minutes (eg. epan16 and geant) and a few hours (eg. the newyork network with 3h40m). These are all networks of small/medium dimension. For a network of larger dimension (the germany50 network), the problem remained unsolved after a few days of execution.

As for the heuristics, they can take between a few seconds for the smaller networks and a few minutes for the larger networks. As expected in terms of execution times, the use of the heuristics is much more advantageous for larger size networks. In fact, for the germany50 network, for which an exact solution could not be found for problem 1 (the quickest for the other networks) even after a few days of execution, it was possible to find an approximate solution in about 30m with metric $\{C\}$ (depending on the value of δ).

Considering the results, it is noticeable that the telia-sonera network has a different trend of results, when compared to the other networks. The fact that this is a very sparse network may help to explain the disparity between the results in Table 6 and the results for the remaining networks. For metric $\{B\}$, we could not even get any feasible solution (*i.e.* a spine with the WPs and edge-disjoint BPs for all the demands) among the first $|\mathcal{N}| \cdot |\mathcal{E}|$ trees found by the used $\mathcal{K}$-shortest trees enumeration algorithm. A metric that managed to find results equal to the exact ones was metric $\{A\}$, unlike what happened for the other networks. Note that metric $\{A\}$ does not take into consideration the topological structure of the network, as it disregards the centrality of the edges. Therefore, it works well for sparser networks, for which it is not possible to identify elements with greater centrality. Metric $\{D\}$ with high δ should allow to take into consideration a larger number of shortest paths in the calculation of the cost (24). An appropriate value for δ was close to $2 * \Delta_M$. With a large value of the tuning parameter α (unlike what happens in other networks), we are decreasing the importance of more central edges (which appear in the shortest paths). Therefore, the created trees from the costs $\{D\}$ should tend to produce longer paths for the node pairs, which is appropriate for sparser networks. In this case metric $\{D\}$ manages to find a solution equal to the optimum.

For the other networks, the results are quite different from these. Unless otherwise stated, the following comments regarding the analysis of results hold for the other networks (*i.e.* except telia-sonera).

The metrics which consistently lead to the best results for both the performance measures (A_{a}^{WP} and A_{m}^{WP}) are metrics $\{C\}$ and $\{D\}$ (only for the polska and the epan16 networks).

For the least sparsed networks, metric $\{C\}$ tends to lead to the best results, as the trees tend to include more central edges with a high node degree. For these networks, there is no need to consider a metric such as $\{D\}$ that leads to trees with longer paths for each node pair so that edge-disjoint BPs may be found.

The behavior of parameter δ in metric $\{C\}$ depends on the network. For most of the networks, it seems that a δ between Δ_a and Δ_M works better, which means that in the calculation of expression (23), it suffices to find the shortest paths and the paths with length close to these ones for most of the demands.

For the polska and epan16 networks, metric $\{D\}$ (with appropriate $\delta \geq 2{*}\Delta_M$ and low α) found solutions with A_{a}^{WP} and A_{m}^{WP} equal to the respective exact value.

For germany50, the exact results are not known. Still, metric $\{C\}$ is the one that led to the best results of the two performance measures.

For newyork, none of the variants of the heuristic managed to find results equal to the exact ones. For this network, we notice that there is a long edge that is part of the spine in the optimal solution. As the metrics considered in the heuristic focus on finding shortest paths for each demand (for subsequent calculation of the edge costs to be used in the tree enumeration algorithm), this very long edge is seldom selected to be in the spine. This is the reason why the optimal solution could not be found for this network. If more trees were considered (and notice that in this network only 5.4E-8 – see Table 1 – of the total possible number of spanning trees were considered), then eventually trees including this edge should appear and the results should be better. In Figures 1-2, the variation of the WP availability measures is displayed as a function of $\underline{\delta}$ [km], corresponding to the value of δ in metric $\{C\}$ and for two different numbers of trees. It is noticeable that with more trees the heuristic manages to find solutions with better values for both availability measures. Obviously considering more trees will entail an increase in the running time of the heuristic, which is not desirable.

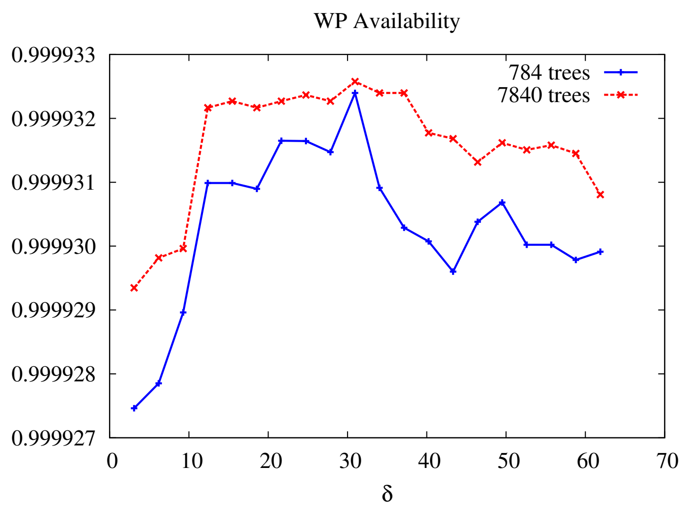

Fig. 1. newyork network: A_a^{WP} for metric $\{C\}$

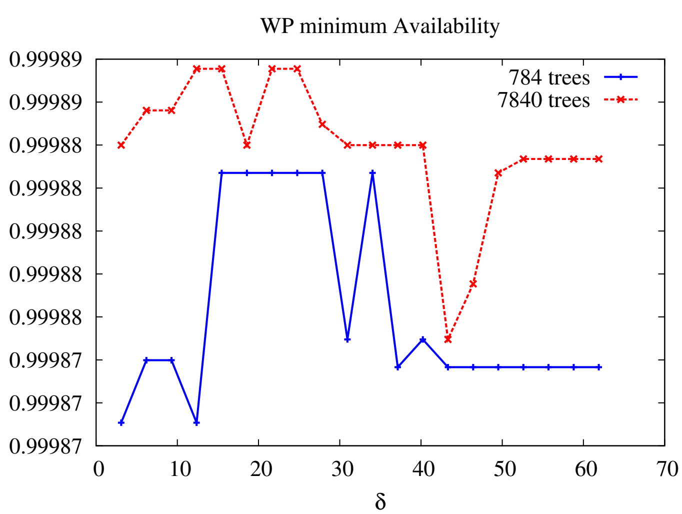

Fig. 2. newyork network: A_m^{WP} for metric $\{C\}$

The main conclusion is that enumerating the first $|\mathcal{N}| \cdot |\mathcal{E}|$ trees in non-increasing order of the centrality metrics $\{C\}$ and $\{D\}$ (with appropriate δ and low α) should allow us to find solutions with the exact value (or close to it) of the availabilities A_{a}^{WP} and A_{m}^{WP}, in a short time (when compared with the execution of an exact algorithm), in particular for large networks.

For the smallest network (polska), solutions with the exact value of the availabilities can also be found with metric $\{B\}$. For this network, a solution with an exact value was also found for metric $\{D\}$ with $\alpha = 0.0$, which is similar to metric $\{B\}$.

Metric $\{D\}$ is a variation of metric $\{C\}$ which should allow to find more edge-disjoint paths. Therefore, a smaller number of possible spanning trees is discarded, as it is more likely to find edge-disjoint path pairs for all the demands. This is noticeable in the tables, where the percentage of discarded trees is shown. Except for the polska network with $\alpha = 0.0$, the percentage of discarded trees is always higher for metric $\{C\}$ than for metric $\{D\}$. For the telia-sonera, this is especially critical as it is a sparse network: for metric $\{C\}$ only a small number of admissible trees were found for many instances of δ, but it was possible to find more admissible trees and better solutions for metric $\{D\}$.

For the newyork network, which is the least sparsed, it was always possible to find an edge-disjoint path pair for all the demands (0% of discarded trees). Although the germany50 network is not a sparse network, it presents a high number of discarded trees. This is due to some specific demands for which the source and/or the destination are nodes with degree 2. For these demands, it is difficult to find edge-disjoint BPs considering that the WPs are in a spanning tree (the spine).

Metric $\{A\}$ tends to present the worst results. Note that metric $\{A\}$ disregards the centrality of the edges, leading to results where the WPs in the spine tend to be longer which leads to worse availabilities for the WP.

For the epan16 and newyork networks, it was not possible to find any solution (among the first $|\mathcal{N}| \cdot |\mathcal{E}|$ trees) with a value of A_{m}^{WP} equal to the exact one. For the other networks, the solution with the best A_{m}^{WP} tends to be found after the solution with the best A_{a}^{WP}. This shows that the algorithm for enumeration of $\mathcal{K}$ trees in non-increasing order of a centrality cost metric tends to favour the solutions with the best A_{a}^{WP}. A different tree enumeration algorithm based on finding the trees with the edge that causes the smallest bottleneck in the tree might be a possibility for favouring trees with a better A_{m}^{WP}. With the current tree enumeration algorithm, it would be necessary to consider a larger number of trees to be able to find the solution with best A_{m}^{WP}.

5 Conclusions

In this work, we focus on the topological structure of a network taking into account centrality measures to select a high availability spine to be used as the WP for each demand. Considering an edge-disjoint BP for each demand, the obtained path pair provides end-to-end protection for critical service demands in the network. An exact formulation to design the spine according to the most available WPs is proposed and solved for small instances networks.

Different centrality measures were studied and used in a heuristic approach based on the enumeration of spanning trees in non-increasing order of centrality costs. As the results show, the centrality measures lead to solutions with high availability. Even if a small number of spanning trees was considered, it was possible to find the optimal solution in most of the tested networks. These centrality measures may be used in the context of other approaches for devising the spine, possibly using meta-heuristics for a more efficient calculation of appropriate spanning trees, leading to a higher availability, namely in terms of the availability of the path pair.

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