Abstract

High-speed networks nowadays relay on fibre optics. Therefore, in case of a network failure the operator should react as fast as possible to minimise the loss of data. For this reason the network fault tolerance becomes more and more important. Many papers deal with designing fault tolerant networks [1,2,3,4]. These papers focus on establishing networks or configure them in an optimal way. Here a different approach is proposed.

What should be done if connections between nodes do not reach a required level of reliability? The focus of our work is how to extend existing links and nodes of telecommunication networks to achieve this level of reliability. A three-phase method (IRE) is proposed: (1) first, try to find redundant paths within the existing link capacities; (2) second, extend the capacities of existing links if needed; (3) third, extend the topology of the network, that is to install new links if needed and possible. The running time of this polynomial algorithm is less than a minute for the Pan-European transport network (29 nodes) and less than two hours even for a heavy loaded Hungarian network (90 nodes). The algorithm gave efficient results for both studied networks.
HOW TO EXTEND A NETWORK TO REACH AN AIMED LEVEL OF RELIABILITY?

Introduction

Reliability is one of the most important performance criteria, which characterises telecommunication network quality. Significant efforts are being made to construct a network as reliable as possible. An integer programming based method is proposed for SONET/WDM ring networks to determine the number of redundant components and wavelength units necessary to achieve a guaranteed level of survivability [4]. Unfortunately, this integer programming based method has very long running time, and it is limited to smaller networks. A tool to generate networks and a tool to evaluate the reliability of multilayer networks are described in [5]. In [6] the availability to cost ratio is compared for three protection strategies: unprotected demand, diversity protected demand and hot-standby protection of transmission system (1+1).

Accordingly, in the literature methods are presented to evaluate the reliability of an existing network [7] and there are many known methods to increase reliability [1, 8]. But there is no known general and fast heuristic method that advances the reliability of the networks over an aimed level. We propose a three phase, iterative heuristic method which has been worked out during the cooperation between Hungarian Telecommunication Operator PanTel, and the Budapest University of Technology and Economics. The method proved to be very efficient even for large, 100-node SDH networks. It can be applied for ATM and WDM networks as well.

Component and Connection Reliability Modelling

In this section, we describe the reliability analysis of SDH and WDM network components and connections [9]. The value of reliability \((R)\) gives the probability that an item will carry out its required mission. Mean time to repair \((MTTR)\) is the total corrective maintenance time by the event of a failure to the total restore of the item. Mean time to failure \((MTTF)\) means the average elapsed time between two failures of the item. The reliability of the system can be expressed by the term \(R = \frac{MTTF}{MTTR} \times MTTR\).

In this case of Series Configuration the system is composed of \(m\) independent subsystems in series. If any one of these subsystems fails, the entire system fails. The Parallel Configuration is composed of \(n\) independent subsystems in parallel. At least one subsystem must function successfully for the system’s success. The \(k\)-out-of-\(n\) Configuration is good if at least \(k\) of its \(n\) units is good. \(N+1\) Configuration gives the reliability of one unit that shares one redundant unit with \(N-1\) other identical working units. Expressions for these reliabilities can be seen in Table 1, where \(R_s\) denotes the system reliability and \(R_j\) the reliability of the \(j\)th subsystem.

The node of a telecommunication network is divided into two parts from the reliability point of view (Fig. 1): the equipment and the traffic cards. If the equipment is disrupted then all links adjacent to it breaks down. If one of

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Expression</th>
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<tbody>
<tr>
<td>Series Configuration</td>
<td>(R_s = \prod_{j=1}^{n} R_j)</td>
</tr>
<tr>
<td>Parallel Configuration</td>
<td>(R_s = 1 - \prod_{j=1}^{n} (1 - R_j))</td>
</tr>
<tr>
<td>(k)-out-of-(n) Configuration</td>
<td>(R_{k/n} = \sum_{i=k}^{n} \binom{n}{i} R_i (1 - R)_{n-i})</td>
</tr>
<tr>
<td>(N+1) Configuration</td>
<td>(R_{N+1} = \sum_{i=1}^{N} \min(1, \frac{i}{N}) \left( \frac{N+1}{N} \right) R_i (1 - R)_{N-i})</td>
</tr>
</tbody>
</table>

Table 1: Reliability of (a) Series (b) Parallel (c) \(k\)-out-of-\(n\) (d) \(N+1\) Configuration
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the traffic cards get in failure state then only the one connected is broken. Consequently, the reliability of an equipment is constant, while the reliability of a link consists of a fix (traffic card), and a length-dependent part. The length-dependent part is proportional to the length of the link.

Reliability of a single path - between two distant nodes - is the product of all link and equipment reliabilities that are adjacent to the path (1). Reliability of a protected path is calculated by the parallel configuration of reliability of a single path (2).

Nodes that are connected to the ring by merely one link are called leaves. Leaves cannot be fully protected. Reliability of a partial protected path (e.g., if source or destination node is a leaf) is the product of the common and the separated reliability: $R = R_{\text{common}} R_{\text{separated}}$. Where common reliability ($R_{\text{common}}$) is the product of the reliabilities of the elements that are used by both the working and the protection path:

$$R_{\text{common}} = \prod_{j \in \text{common}} R_j$$

and the separated reliability is the parallel configuration of the working and protection reliability

$$R_{\text{separated}} = 1 - (1 - R_{\text{work}}) (1 - R_{\text{prot}})$$

$$R_{\text{work}} = \prod_{j \in \text{path in working path only}} R_j$$

$$R_{\text{prot}} = \prod_{j \in \text{path in protection path only}} R_j$$

The term path availability is also common for the reliability of a path. The term network availability is common for the probability that certain number of paths is in up-state, i.e., is working. Two main measures of the network are considered, which characterises telecommunication network quality: first, the average reliability ($R_{\text{ave}}$) is the mean of all connection reliabilities; second; the minimum reliability ($R_{\text{min}}$) is the minimum of all connection reliabilities.

**Problem Formulation**

The formulation of the problem is as follows. The topology of the existing network, link capacities, demand matrix, link and node reliabilities are given. The reliability value is constant for nodes, and it consists of constant and marginal value for links. Our aims are (1) to determine both the working and protection paths, (2) to determine for each link how much capacity should be added to it so that each working and protection path can be routed, (3) to determine the minimal number of new links to be installed. The objective is to use as few
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resources (link capacities) as possible. The additional constraint is the given degree of minimum reliability $R_{\text{min}}$ to achieve.

Methods for Solving the Problem

This problem can be formulated and solved optimally by an Integer Linear Program (ILP). The problem is NP-hard, therefore it is computationally very intensive, i.e., it is nearly impossible to get a solution for a large or even a medium size telecommunication network. Therefore, it is reasonable to search for heuristic methods. Our new heuristic is based on two methods: first, on the Iterative Capacity Splitting (ICS) [1], and second on a randomised method, which is based on the method proposed by M. Pióro called Simulated Allocation (SA) [10].

Iterative Capacity Splitting

The network is modelled in standard way as either a directed or undirected graph. The traffic demands are the commodities. The Iterative Capacity Splitting (ICS) algorithm [1] determines for each node pair two independent paths, which do not violate the capacity constraints. It consists of two main phases that are iterated:

1. In the first phase one path is determined for each demand solving the unsplittable multicommodity flow problem by integer programming or by a combinatorial algorithm that gives results very close to the best possible and runs 1-2 orders of magnitude faster.

2. In the second phase we determine the secondary path which is independent of the first one, i.e., disjoint. The easiest way of completing this task is first to delete temporarily the working path (the edges of the working path when edge disjointness is required or edges of the working path and all edges adjacent to vertices of the working path except for the two end-vertices when vertex disjointness is required). Second to find all links which do not have enough capacity to accommodate the traffic of the considered commodity and to delete them also temporarily. Third, to use a shortest path algorithm for finding the backup path, and then to allocate capacities and restore the deleted edges.

3. Iteratively repeating phases 1 and 2 capacities are being allocated to working and backup paths.

The proposed heuristic Method: Iterative Reliability Enhancement (IRE)

The flowchart of the Iterative Reliability Enhancement algorithm can be seen in Figure 2.

First phase. The first step of the algorithms is to route as many protected paths as possible. This is done by the ICS method that gives approximate results for an NP-complete problem in polynomial time. In the first phase of ICS working routes are searched so that each link capacity is to be decreased to the half ($w_l = c_l/2$). When not all commodities can be routed then increase the working capacity $w_l$ for each link $l$, e. g., by 10% until this step succeeds. In the second phase find as many protection routes as possible. The advantage of this method is that it finds working routes for all demands, and as many protection routes as possible.
Second phase. In many practical situations finding a protection path conflicts the capacity constraints. It means that the demands cannot be accommodated by available capacities. The question of the second step is how to extend existing links of telecommunication networks such that the extending cost should be minimal? Costs of a capacity extension can be lower if there is enough fibre installed in the ground, and only the equipment at the ends of the span are to be installed. The cost of extending a link is higher if new cables are to be laid.

For capacity extension a greedy algorithm is proposed: Take the demand with the lowest current reliability value ($R_d$). Find a protection route for that commodity without capacity constraints. Repeat this procedure for $k$ commodities while there is any connection, which has reliability $R_d < R_{\min}$ and an independent protection path can be found for it. Calculate new required capacity ($c_i'$) for each link affected by the new paths, and extend all links accordingly (e.g., by a new STM-16 in case of an SDH network, but at least by $c_i' - c_i$). If some link capacities were increased in this phase, repeat the procedure from the first phase such that links are utilised smoother. Repeating the first phase also takes the advantage that link capacity extension can provide shorter paths.

Third phase. The third step of the algorithm is to protect nodes or regions that are connected to the network by a single link. Single links deteriorate the reliability value because in case of a single link failure the whole region is cut from the network. So if it is needed, those regions are connected to the network with a second link. This step depends strongly on the geographical capability of the region, e.g., location of rivers, railways, and mountains. Many research activities pay considerable attention to the problem of topological design [2] and connectivity augmentation [11]. It can be solved either by algorithmical tools or by human intervention or combining them.

Numerical Example
The performance of the IRE algorithm is investigated on two more or less realistic networks. Figure 2: Flowchart of the IRE algorithm The first one consists of 26 nodes, which is an extended topology of the European Optical Network (EON). Seven more cities, Budapest, Bratislava, Warsaw, Helsinki, Vilnius, Riga,
and Tallinn are added to the network introduced in [12]. The topology and link capacities can be seen in Figure 3 where one capacity unit corresponds to 2.5Gb/s. For simplicity reasons demands between all node pairs are of one unit. There are two "leaf" cities: Warsaw and Helsinki that can not be protected. The second network is the modified backbone network of PanTel that is a ring-based SDH one with 90 nodes of which 9 are "leaves".

Considering EON network in the first phase for all 325 commodities can be found a working path but only for 276 of them a protection path. In the second phase $k=5$ is a good compromise and if capacity extension is necessary then it is increased by $c=10$ units. Six cycles were necessary to obtain protection paths for all commodities except the unprotected links Helsinki-Tallinn and Bratislava-Warsaw. Commodities with end points in Helsinki or Warsaw are partially protected, i. e., protection routes are searched with end point Tallinn or Bratislava instead.

In the third (topology extension) phase Warsaw has been connected to Berlin while Helsinki to Stockholm. The new configuration was successful for all commodities. The changed link capacities can be seen in Table 2. It has been assumed that both the equipment reliability and the constant link reliability are equal to 99.9999%. Link cuts happen in 300 km once a year and are repaired within at most 4 hours. The increase of minimum (MIN) and average (AVE) reliability can be seen in Figure 4. In the first four steps the existing edge capacities have been extended. In this phase the minimum reliability has been enhanced from 99.7062% to 99.7292% and the average reliability from 99.9763% to 99.9895%. The minimal reliability has improved significantly in the topology extension phase (Step 5) to 99.9972%. The average reliability reached 99.9992%. The algorithm has been applied with different traffic loads. Load1 means that the amount of commodities is increased by 10% and load2 means it is increased by 25% relative to the fully protected instance. The running time (on Pentium 200MHz, 80Mb memory, Windows NT) for EON-29 was 58 seconds for load1 and 66 seconds for load2, while in case of the Hungarian network 83 and 104 minutes for load1 and load2 respectively.
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<table>
<thead>
<tr>
<th>Link</th>
<th>Old Cap</th>
<th>New Cap</th>
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<tbody>
<tr>
<td>Paris-Zurich</td>
<td>80</td>
<td>130</td>
</tr>
<tr>
<td>Paris-Milan</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Zurich-Milan</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Zagreb-Vienna</td>
<td>80</td>
<td>110</td>
</tr>
<tr>
<td>Vienna-Berlin</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Berlin-Warsaw</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Stock-Helsinki</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>Moscow-Tallinn</td>
<td>80</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2: Changed link capacities on the EON network

Figure 4: Average (AVE) and minimal (MIN) reliability for EON-29 in 5 steps

Conclusion

The reliability analysis of SDH and WDM network components and connections has been described. A three phase, iterative heuristic method has been proposed, that advances the reliability of networks to a certain level. The obtained results can be used efficiently for extension of even large-scale networks, consisting of 100 or more nodes. The algorithm runs in polynomial time. The demonstrations on two real-life networks of practical interest have shown that the IRE algorithm guarantees high reliability while keeping costs as low as possible.

References