



BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
DEPARTMENT OF TELECOMMUNICATIONS

Assessing and Guaranteeing Availability in Networks with Multiple Failures

Ph.D. Thesis summary

by

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1 Introduction

Service outages in telecommunications networks represent higher risk than ever before because of the unprecedented extent of traffic concentration on high capacity links and because of the unacceptable potential economic consequences. Moreover, an ever-growing part of revenues of network operators depends on the compliance with service level agreements (SLA's) that are part of service contracts signed with customers. Therefore, the improvement of the survivability of telecommunications networks has received increased attention recently.

As a result of significant amount of research in the field today there is a plethora of various resilience schemes that attempt to mitigate the impact of component failures. The majority of works on resilience schemes quantifies failure resilience of connections as the highest number of components that may fail at the same time so that the connection is restored by means of diversion to backup paths. However, this quantification is hard to translate to guarantees on downtime, i.e., availability guarantees. These guarantees are important because service level agreements are based on them, as they are easy to interpret by customers. In addition, failure multiplicity based categorization does not provide sufficiently fine control on the trade-off between resource consumption and the provided level of availability.

The majority of protection methods proposed in the literature target at routing single failure robust connections, that is, they only guarantee the survival of the connection in case of single component failures. This approach is structurally reasonable and economic with respect to resource usage and, somewhat surprisingly, usually provides robustness against a significant portion of failures of higher multiplicity, as well [6].

With the growth of networks in capacity, scale and number of components, the probability of failures of higher multiplicity increases significantly (see Figure 1). Consequently, applications with higher availability requirements do need probabilistic guarantees that also apply to multiple failures.

Reliability theory has shown long ago that problems related to connection availability computation are hard to solve in the general case [18]. One may thus resort to examining special cases when it is possible to compute exact values, or try to devise conservative estimation methods that may be used for bounding connection availability. A bound is called conservative if it is a lower bound that always avoids excess and its value remains below the estimated quantity. An estimation method is called conservative if it yields conservative bounds.

One may pursue different approaches to bound the results of the exact computations. If the network is modeled as a system of finite states then state-space sampling methods may be applied, such as the well-known Monte Carlo method [4], stratified sampling [2] or adaptive approximation [15].

A failure stratum in the failure state space is usually defined as the set of failure states in which the number of simultaneously failed components equals a certain value. For example, the failure states with exactly two failed components constitute

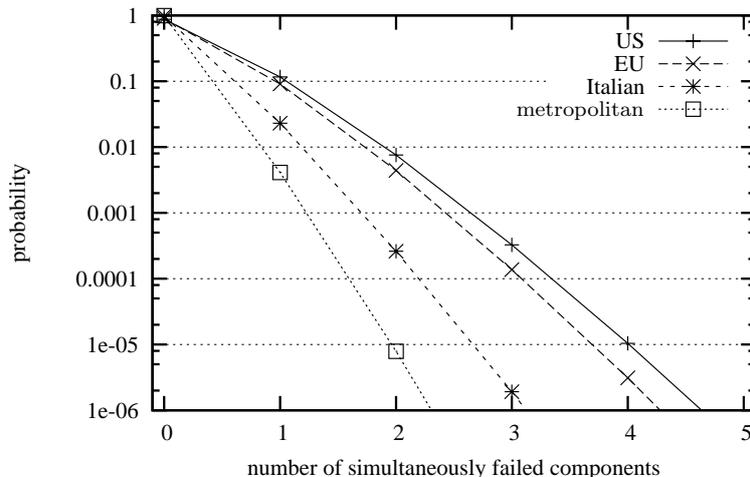


Figure 1: Probabilities of failures of different multiplicity in different networks.

a failure stratum. Computing the total probability of all failure states that belong to the failure stratum, termed as failure stratum probability, is important in order to support network analysis methods that are based on the principle of state space sampling.

Another approach to pursue is to derive bounds on connection availability using general methods. The principle of inclusion-exclusion is often used for computing bounds if the desired value is a probability [5]. However, one issue with the application of the inclusion-exclusion principle may be the need to specify or compute joint probabilities of events. If backup resources are shared in telecommunications networks then the events to deal with are often not independent, and due to the lack of field data and the difficulty to estimate such probabilities the practical applicability of general methods is limited. Nevertheless, by means of taking advantage of the knowledge on the structure of the problem one may devise specific methods for obtaining bounds. These bounds are especially important when connections have to be established with availability guarantees.

When backup resources are shared among multiple connections and the impact of multiple failures may not be neglected, an on-line call admission control algorithm, upon arrival of a new connection demand, not only has to check that there are resources available for routing the incoming connection demand so that its availability requirement is satisfied, but it must also check that the new connection demand does not decrease the availability of already active connections below their respective availability requirements.

It is an area hardly covered by literature so far. [13, 16, 19, 22, 23] address connection establishment with availability guarantees in both network dimensioning and dynamic traffic contexts with shared backup resources. However, as they are based on non-conservative availability estimation methods, their guarantee on connection availability is not a provable guarantee.

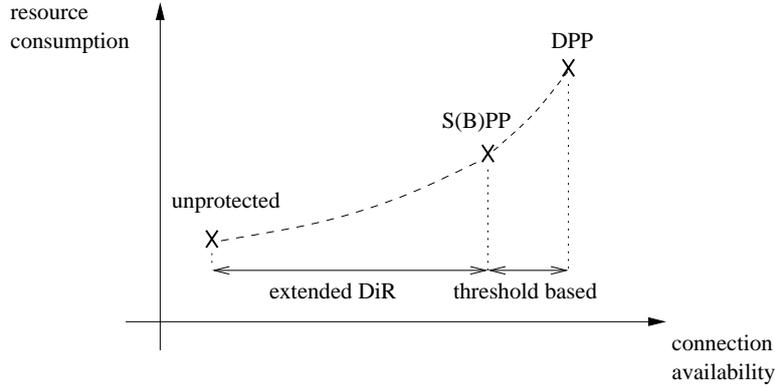


Figure 2: Positioning of provisioning methods proposed in the thesis.

[21] proposes a network dimensioning method based on the conservative connection availability estimation method in [1]. However, the problem of dynamic connection provisioning with availability guarantees is defined only as a future research direction therein. Another network dimensioning method is proposed in [20], which is based on a conservative connection availability estimation technique. However, as the objective of [20] is to ensure structural resilience against multiple failures, the practical applicability of this method is limited by its complexity and the fact that it implies a network topology of high connectivity.

To sum up, several publications address the establishment of connections with guarantees on failure resilience. The guarantees often appear as the highest component failure multiplicity that connections can withstand, and only a few works define availability guarantees among the objectives. The key to guaranteed availability is a conservative method for connection availability estimation. To the best of the author's knowledge so far only two such methods have been published [1, 20], none of which is directly applicable to a dynamic traffic scenario. It is, therefore, interesting to investigate the problem.

2 Research objectives

The general objective of the thesis is to overcome the discussed shortcomings of current work related to (connection) availability computation and connection provisioning with guaranteed availability.

A general network model is considered in which there are independent, two-state components. Both links and nodes are considered to be failure-prone except where due notice is made in order to simplify the discussion.

Based on this network model the first goal is to propose a computationally efficient algorithm for computing the probabilities of failure strata. Such an algorithm may then be applied to systems of known structure to demonstrate that probabilities of failure strata may be computed efficiently exploiting knowledge on system structure.

The main goal of the thesis is to propose methods for dynamic connection provisioning with availability guarantees based on shared (backup) path protection (S(B)PP) that are capable of keeping resource usage lower than that of dedicated path protection (DPP). The differentiated reliability (DiR) principle is a suitable candidate for differentiation of connection availability (for a detailed description of DiR please refer to section 4.2). By means of extending the DiR principle to multiple failures for providing absolute probabilistic guarantees it is possible to scale connection availability from the unprotected case to the shared backup path protected case with full backup resource sharing.

In order to provide availability guarantees beyond these, additional limitations have to be introduced on the sharing of backup resources. This may be accomplished by introducing a threshold parameter in the connection admission control algorithm. In return for the higher expected complexity this solution has the potential to offer higher availability guarantees (see Figure 2).

The importance of node failures is often overlooked or deemed insignificant in the literature. It is therefore an additional goal of the thesis to analyze the impact of node failures on end-to-end connection availability in all-optical networks.

Another goal of the thesis is to address the applicability of the proposed algorithms and methods.

Even though the proposed solutions may be generalized, it is out of the scope of the present work to devise and discuss in detail potential ways to guarantee connection availability with other protection and/or restoration methods. Elaborating solutions that are directly applicable to other networking technologies — including those based on packet-switched operation — also remains out of the scope of the thesis, as well as the assessment of the difference in between *guaranteed* and *actual* connection availability. QoS parameters except for availability and call blocking, such as recovery time, are not covered by this thesis either. Optical networks with wavelength conversion capabilities are neither addressed. Instead, these points are set forth as future research topics.

3 Research methodology

First, the identified open problems are formulated using mathematical notation. This initial step is inevitable for accurate and unambiguous description of conditions, concepts and relationships.

Models are then constructed using the introduced notations with help of graph theory and probability theory. Elemental techniques and results of algebra and queuing theory are also applied whenever necessary to derive either exact or approximate solutions or to express performance parameters. Some of the encountered problems are proved to be computationally difficult using the results of computation theory.

The proposed provisioning methods are tested by means of simulations.

A simulator is implemented based on the general principles of event driven simulation [10] and parameters of the simulations are chosen to reflect networks of reality. Simulation results are presented with appropriate confidence intervals obtained using statistical methods.

Conclusions are drawn based on either mathematical proofs or simulation results, and limitations to the applicability of the proposed methods is also discussed.

4 New results

Contributions of this thesis are grouped as follows. The first group of theses deals with exact computation of multi-component failure stratum probabilities. The second group is about the extension of the DiR principle to include failure-prone nodes and to provide absolute connection availability guarantees. Finally, the third group of theses is related to a sharing threshold based connection provisioning algorithm that may guarantee higher levels of availability than the extended DiR method.

4.1 Efficient computation of multi-component failure stratum probabilities

Thesis 1.1 ([J1]). *I have proposed a new algorithm for the computation of multi-component failure stratum probabilities. The complexity of the proposed algorithm is $O(KN)$, where K is the number of strata and N is the number of components in the system.*

The complexity of the algorithm available in the literature for the same purpose [2] is $O(K^2N)$, because it derives a recursive formula for each of the failure strata and evaluation of individual formulas require $O(KN)$ operations each. Therefore, the algorithm proposed in Thesis 1.1 outperforms the algorithm in [2].

The algorithm proposed in Thesis 1.1 assumes a general reliability model of the system, in which there are independent two-state components. These components may either be *operating* or *failed*, and for each component the probability that at any time the component is in the failed state is assumed to be known.

The fundamental idea of the algorithm is to consider the failure stratum probabilities as a probability distribution with a discrete support. Using the probability-generating function of this distribution the convolution to be carried out when unifying component sets may be computed as a multiplication of polynomials. If only the probabilities of the first K strata are to be computed then the multiplication should be carried out (mod z^{K+1}).

If the system to be analyzed can be modeled with the conditions described above, then the algorithm of Thesis 1.1 can be applied to obtain the failure stratum probabilities. Therefore, it is a tool useful for general reliability modeling, and may be applied outside the networking context, as well.

Thesis 1.2 ([J1]). *I have shown that if the structure of system to be modeled is composed of series and parallel combinations of subsystems then the overall failure stratum probabilities may be derived easily using the failure stratum probabilities of the subsystems.*

Thesis 1.2 is in fact an extension of the well-known method for determining the availability of series-parallel systems to failure stratum probabilities. In other words, the former becomes a special case of Thesis 1.2.

This result is relevant in cases when analysis results of subsystems are available and end-to-end system wide characteristics have to be derived. As an example consider a network that is divided into domains, and the division complies with the conditions above. If end-to-end performance analysis is necessary and state space sampling is used then Thesis 1.2 helps decide how to sample failure states if a stand-alone analysis of domains is already available.

4.2 Extension of the DiR method to node failures and absolute probabilistic guarantees

The basic idea of the DiR concept [11] is to change the assumption that each connection requires protection against every single failure along its working path. If availability requirements of connections are lower, but high enough that a single working path does not suffice, the backup path may be necessary to withstand the failure of only a subset of links used by the working path. This leads to somewhat relaxed sharing rules, which in turn yields increased capacity efficiency, or lower blocking in a dynamic traffic scenario. The DiR concept specifically addresses probabilistic guarantees, yet only for single failure scenarios, i.e., probabilistic guarantees remain conditional.

The following results assume a single-layer wavelength-routed WDM network model.

Thesis 2.1 ([J2, C5]). *I have extended the DiR principle applied to shared (backup) path protection (SPP-DiR) in order to include node failures and to provide absolute connection availability guarantees (SPP-eDiR).*

The basis of the extension is a simple yet conservative connection availability estimation technique, which is applicable to on-line connection provisioning. A connection is considered to be disrupted if any of the following conditions are fulfilled:

- any of the unprotected links or nodes of the working path fails, or
- any of the protected links or nodes of the working path fails and there is at least one failed network component that is not used by the working path.

This bounding method is simple to implement, and inherently ensures that newly admitted connections do not violate availability guarantees of already admitted ones.

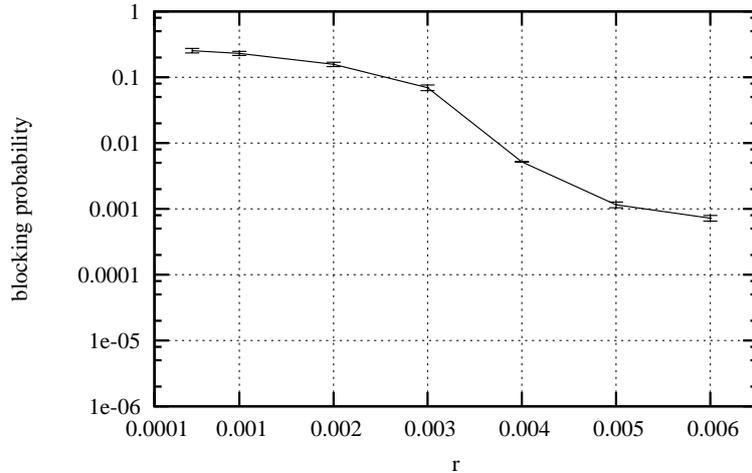


Figure 3: Blocking in the Italian network as a function of the r availability requirement.

The performance of the SPP-eDiR method is illustrated on Figure 3. The availability requirement r is interpreted as the maximum allowed asymptotic unavailability of connections, often referred to as *downtime ratio* (DTR). Thus, lower values of r mean better availability guarantees. The figure demonstrates that when the availability requirement is relaxed, in other words, when the value of r is increased, the algorithm is capable of significantly decreasing the ratio of blocked connection requests.

network	r_{\min}	
	SPP-eDiR	DPP
US	0.00236885	0.000586236
European	0.00133932	0.000301568
Italian	0.0000754779	0.0000212594
metropolitan	0.00000374488	0.00000192799

Table 1: Best feasible availability guarantees for different networks without node failures for SPP-eDiR and DPP.

By means of exploiting *a priori* knowledge about the candidate path set to be used by connections it is possible to determine the best potential availability guarantees (r_{\min}) that may apply to any connection in the network. These values are presented in Table 1 for different network topologies without node failures for SPP-eDiR and for DPP. Obviously, assuming failure-prone nodes increases the presented values.

The performance comparison of SPP-eDiR, DPP and the method introduced later in Thesis 3.1 may be found in Figure 6 (for the discussion please refer to section 4.3). Additional results obtained with the SPP-eDiR method are presented in section 5.2.

Thesis 2.2 ([J2]). *I have proved that the routing and wavelength assignment*

problem to be solved when using the SPP-DiR method for connection provisioning is NP-Complete.

The idea of the proof is to reduce the problem to routing and wavelength assignment using shared (backup) path protection, which is already proven to be NP-Complete in [17]. Note that the proof applies to the SPP-eDiR method, as well. This result justifies the proposal of a heuristic solution to the RWA problem that arises during the application of SPP-eDiR.

4.3 A threshold based algorithm for higher availability guarantees

As seen from Table 1, there is a significant difference in between feasible availability guarantees when only the backup sharing constraints of SPP are applied and when backup resources are dedicated. It is especially interesting to see how this gap may be bridged in networks of continental scale.

Sharing unavailability is defined in this thesis as the increase in unavailability of a backup resource from the viewpoint of a particular connection that derives from the fact that the backup resource is shared with other connections.

If an on-line RWA algorithm can control sharing unavailability for each demand then availability computations become much easier. To facilitate this, a threshold $q_s^{(e,w)}(d)$ is introduced for each link $e \in E$, wavelength w and connection d . If the on-line RWA algorithm enforces that the upper bound on sharing unavailability is always less than $q_s^{(e,w)}(d)$, then

1. $q_s^{(e,w)}(d)$ appears to be a limit that determines the extent to which different demands may re-use the same resource, and
2. $q_s^{(e,w)}(d)$ also guarantees that sharing unavailability of resources is always upper bounded, and, therefore, future connection demands will not decrease availability of already admitted connection demands below their requirements. In other words, time dependence of backup resource availability, an inherent difficulty of a dynamic traffic scenario, is eliminated from the computations.

As a consequence, the sharing unavailability threshold is interpreted as a parameter of the connection provisioning method.

Thesis 3.1 ([C4]). *I have proposed a sharing unavailability threshold based method (ShUT), which is capable of providing better availability guarantees than the SPP-eDiR method, while keeping blocking probability lower than that of dedicated path protection.*

The key to this method is an upper bound on the value of sharing unavailability, which yields a conservative bound on end-to-end connection availability. Sharing unavailability for connection d and backup resource (e, w) may be upper bounded

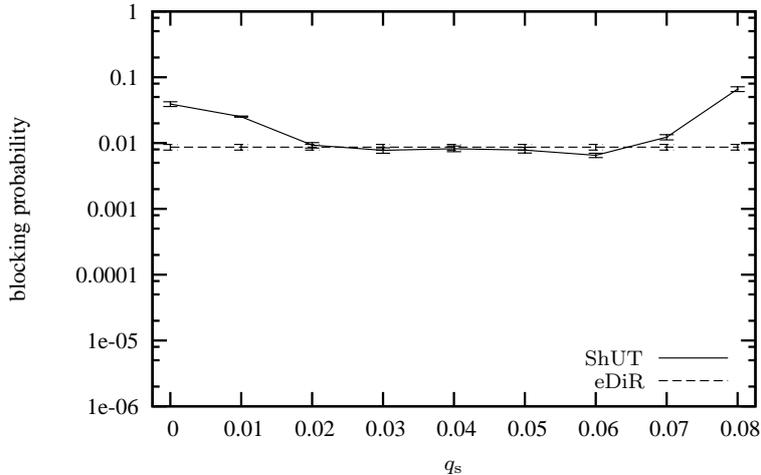


Figure 4: Blocking probability as a function of q_s at $\lambda = 200$, with $r = 0.005$.

by the probability that any failure happens on the working path of any of the connections $d_i \neq d$ that share resource (e, w) with connection d . A conservative bound on connection availability is then obtained by decreasing the availability of backup resources with the value of the sharing unavailability threshold and carrying out computations as if backup resources were dedicated.

The current study assumes a single value $q_s^{(e,w)}(d) = q_s$ that applies to all connections and backup resources, and results are obtained for the European WDM network. λ is the parameter of the Poisson process used for generating random connection request arrivals evenly distributed among the nodes. Connection holding time is exponentially distributed with parameter $\mu = 1$; therefore, the λ intensity equals the network load measured in Erlangs.

As illustrated on Figures 4 and 5 the blocking of the ShUT method depends on the value of the threshold. With an appropriate choice of q_s the blocking may be as low as that of the extended DiR method assuming the same availability requirement (Figure 4). Moreover, if availability guarantees are higher than what is feasible with SPP-eDiR, a good choice of the value of q_s may lead to a blocking probability which is at most half of that of dedicated path protection (Figure 5). In the special case when $q_s = 0$ the ShUT method behaves as dedicated path protection, and the results shown on the figure are obtained using this property.

The curve on Figure 4 resembles the shape of a bathtub. This phenomenon can be explained as follows. As q_s is increased from 0 gradually more and more sharing is possible, which leads to more efficient resource use and lower blocking. If q_s is further increased, some of the paths of longer connections can no longer provide a feasible routing because of the backup resources of seemingly less availability. As a consequence, blocking is increased.

In general, it is quite difficult to predict a good value for the threshold $q_s^{(e,w)}(d)$, especially because optimal network performance probably requires careful selection

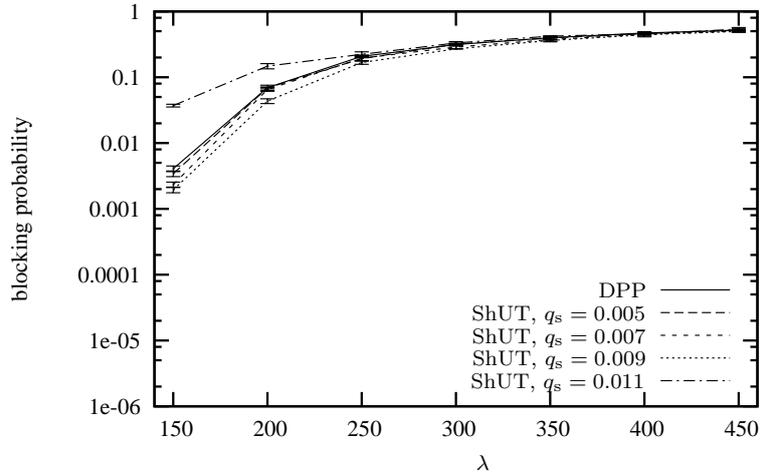


Figure 5: Blocking probability as a function of network load with $r = 0.001$.

of each $q_s^{(e,w)}(d)$ considering the network topology, the candidate path sets and availability requirements of demands. However, if the general problem is restricted to finding a single value $q_s = q_s^{(e,w)}(d)$ so that $r = r^{(d)}$ is also assumed, it is possible to identify ranges of interest.

Thesis 3.2. *I have proposed algorithms to identify the relevant ranges of the value of the sharing unavailability threshold based on a priori knowledge of the candidate path sets. These algorithms help determine good values of the threshold without running an excessive number of simulations.*

An algorithm is presented in the thesis that computes the value of $q_{s,\max}$ with the conditions discussed above. $q_{s,\max}$ is the highest permitted value of q_s so that the availability guarantee r may be fulfilled for any connection in the network. Another algorithm is presented to derive $q_{s,\max S}$, which is the minimal value of q_s needed to enable maximal backup sharing given the sets of path candidates. The output of these algorithms is presented in Table 2 for the European WDM network.

Comparison of the table and the simulation results shows that the estimation of $q_{s,\max}$ is always a good upper limit for the range of interest for q_s . By definition, higher choices do not make sense. However, there is no point in selecting a value that is higher than $q_{s,\max S}$, because that does not increase sharing any further.

r	$q_{s,\max S}$	$q_{s,\max}$
0.0007	0.0815029	0.0063394
0.001	0.0815029	0.0111975
0.0015	0.0815029	0.0193748
0.005	0.0815029	0.0840775

Table 2: Estimations of ranges of interest for q_s in the EU network.

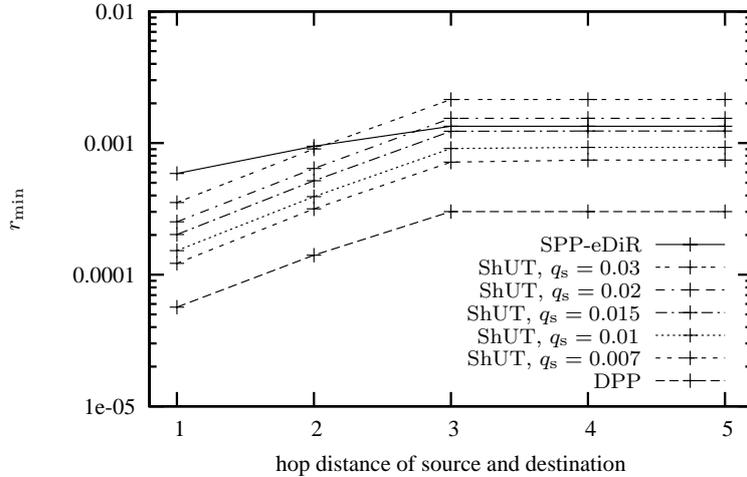


Figure 6: Best guarantees for connections of different length in the EU network.

On the other hand, it seems that there is no need to enable maximal sharing always, which also agrees with the observations made in [C3, C1, J3]. There are multiple arguments that support this, one of which is the same as that of the climbing stage of the blocking probability curve towards higher threshold values on Figure 4. Another argument to consider is that the availability requirement does not always require that each connection uses a backup path. Consequently, the call admission control algorithm may not always attempt to reach a state that is close to the theoretical maximum of backup resource sharing.

[9] defines standard connection availability requirements as a function of physical distance between connection endpoints. Due to the different nature of the estimation methods, the ShUT method potentially performs better than the extended DiR method in this respect, as demonstrated by Figure 6.

With respect to Thesis 3.2, in order to determine the value of $q_{s,\max S}$ it is necessary to solve the following problem, which is also proved to be hard to solve.

Thesis 3.3. *I have proved that determining the largest subset of connections whose backup paths may share resources is NP-Complete even if the candidate paths to be used by connections are known.*

The idea of the proof is to reduce the problem to finding the maximum independent set in a graph (IS). The IS problem is known to be NP-Complete, and a simple greedy algorithm gives a very good solution [12]. The idea of this simple greedy algorithm is adapted in the algorithm that determines the value of $q_{s,\max S}$.

5 Application of results

Careful research work has to address not only the explanation and demonstration of the solutions elaborated for the studied problem, but also the examination of the

applicability of the results. The thesis includes a discussion of the applicability of the new results, out of which here only the most important observations are repeated. In addition, examples are used to illustrate potential and actual applications.

5.1 Limitations to applicability

Maybe the most important problem related to the applicability of on-line connection provisioning methods that require complete network state information for connection admission decisions is faulty decisions due to expired network state information. This general issue was examined with help of a theoretical model [C2].

The model assumes that a general intra-domain link state routing protocol is used for maintaining the link state databases at network nodes, and it yields an upper bound on the probability that call admission decisions are made using outdated network state information. The estimation is based on considering the speed of dissemination and processing of network state information.

The model helps evaluate the performance of real world protocols used for link state database maintenance, which ultimately determines the performance of on-line connection provisioning methods, as well. I have applied the proposed model to analyze the probability of faulty call admission decisions assuming that the applied link state routing protocol is a suitable extension of OSPF (e.g. [7, 8]) [C2].

Figure 7 illustrates the results. Note that the estimated probability is an upper bound; consequently, “real” probabilities are expected to be lower. The load values on the figure are measured in $[1/s]$ as opposed to the normalized scale used earlier.

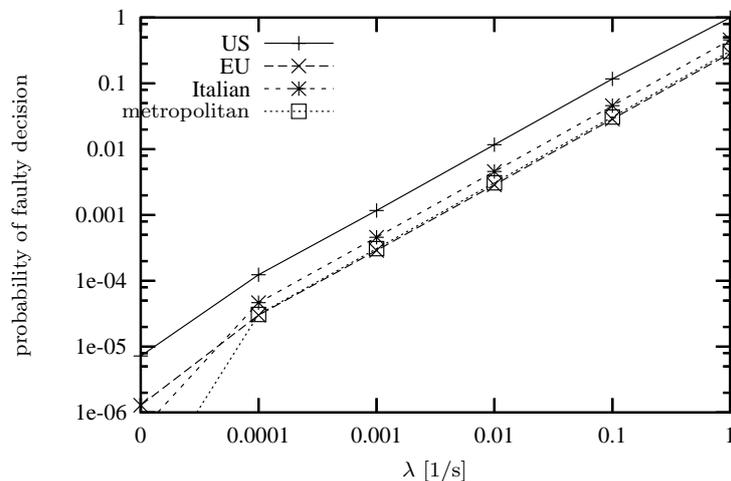


Figure 7: Upper bound on the probability that faulty decision is made at any node in different networks as a function of λ .

The differences between the network topologies are mainly due to differences in connectivity and “diameter” of the respective topologies.

The conclusion is that offered load has paramount significance with respect to the frequency of link state database inconsistency. This is supported by comparing the left end of the curves, which belongs to zero arrival intensity, with the region to the right. If the network traffic is not highly dynamic (overall call arrival intensities are less than 0.001/s), the results suggest that the effect of link state database inconsistencies is not significant. However, in case of more dynamic traffic a more detailed analysis is necessary.

5.2 Application examples

Using the algorithm referred to in Thesis 2.1 I have analyzed the impact of node failures on end-to-end connection availability and blocking probability in all-optical networks using different node architectures and technologies.

An illustration of these results is depicted on Figure 8, where λ equals the network load measured in Erlangs. The three different types of node equipment compared in the figure are the following (in the order of increasing availability): structurally non-redundant micro-electromechanical system (MEMS) based mirror switch, structurally redundant indium-phosphide based intergrated optical switch and structurally redundant MEMS based mirror switch. The equipment choice apparently makes a considerable difference in blocking probability in the metropolitan scale network examined in Figure 8 assuming identical connection availability requirements.

The conclusion of the analysis, which is presented in the dissertation in details, is that in networks of continental scale link failures dominate end-to-end connection availability. Therefore, it is not reasonable to invest in extremely costly and/or redundant node equipment. On the other hand, the architecture and technology of node equipment are significant parameters with respect to feasible availability guarantees in a metropolitan scenario, and an appropriate choice may make a difference of two orders of magnitude in end-to-end availability.

The simulator that implements the sharing unavailability threshold based method has been applied to obtain results as part of the contribution of Magyar Telekom (formerly Matáv), the Hungarian incumbent telecommunications service provider, to the IST project MUPBED of the 6th Framework Programme of the European Union [14]. The main goal of the IST project MUPBED is to integrate and validate, in the context of user-driven large-scale testbeds, ASON/GMPLS technology and network solutions as enablers for future upgrades to European research infrastructures [14].

In addition, the results published in [J1, J3, C1, C2, C3, C5] represent the Hungarian contribution to the COST action 270 of the European Union [3]. COST 270 bears the title “Reliability of Optical Components and Devices in Communications Systems and Networks”. The main objectives of the action are: (1) to develop methods to ascertain and improve the reliability of new types of optical components and devices in communications networks and systems; (2) to study network and component costs, environmental conditions and installation procedures for equipment

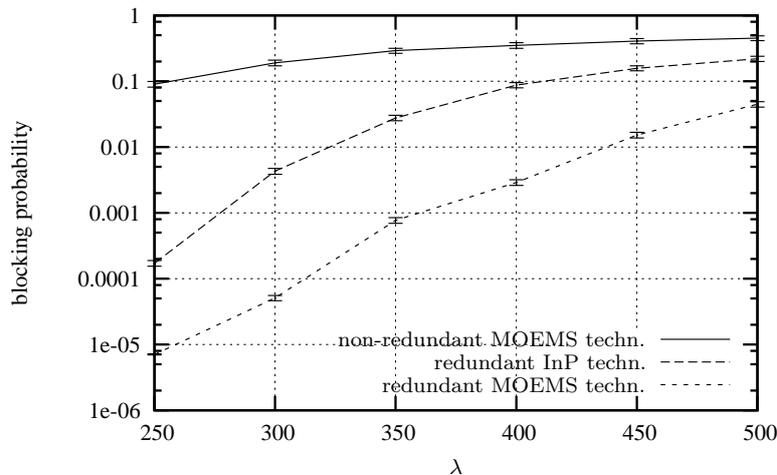


Figure 8: Blocking in the EU network with link lengths scaled to 1:50 as a function of the λ call arrival intensity.

in transport, metro, subscriber access networks and in in-house (local area) networks are included; (3) to transfer the results and experience to standardization bodies.

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