Network Reliability: Models, Measures and Analysis*

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Abstract

The modelling and analysis of telecommunication networks have become more and more important with the evolution of communication technologies resulting in increasing capacities and with the application of several network protection techniques aiming at the provision of high quality services when the network elements apt to random failures.

Several network reliability models have been introduced and many analysis techniques have been developed, however, due to the complexity of the problems many of them have not been solved. The paper presents an overview of the main directions of network reliability analysis and summarizes the critical issues. A possible solution taking into account the multi-layer structure of the networks is described, some bounds for performance indices are introduced and their application is demonstrated.

1 Introduction

The evolution of communication technologies results in continuously increasing capacities and higher concentration of traffic on relatively fewer elements. The failures of these high capacity elements affect the quality of service provided by the network, and therefore, several protection techniques have been developed and implemented in order to ensure resilience to network outages caused by the failure of the components [19].

Due to this fact, the importance of network reliability and the complexity of its derivation is reflected by the vast number of papers devoted to the topic over the past two decades, however, reliability is a very complex measure of telecommunication networks which is difficult to define and to evaluate. Some of the most critical problems concerning network reliability modelling and analysis can be briefly summarized as follows:

- definition of adequate reliability measures with multi-service requirements,
- determination of the possible states of the network with extremely large number of network elements subject to failure,
- determination of the impact of failures on reliability measures in the presence of several applied multi-layer protection techniques.

In the paper, first, the main measures introduced and applied to the expression of network reliability are summarized. In the second part of the paper a basic network reliability model with the usual approximation technique is given. Then, a multi-layer network model with possible lower and upper bounds is described and the efficiency of the method is demonstrated with some numerical results. Finally, the paper is concluded.

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2 Reliability models and measures

Concerning the definition of network reliability, the papers published in this field can be basically classified into four main groups:

1. connectivity measures,
2. maxflow (capacity) measures,
3. multicommodity flow measures,
4. performability measures.

2.1 Connectivity measures

In 70th and early 80th, reliability was considered as the connectivity of the graph representing the network. The network is supposed to be subject to deterministic interventions or random failures. In the first case an intelligent enemy knowing the network structure can cause the disconnection of the network, and the reliability is expressed by the difficulty of the intervention, the connectivity of the graph[1]. In the second case, K a subset of graph nodes is defined, and the most general measure is the K-terminal probabilistic connectivity, which is expressed as the probability that certain connections exist in the graph among the nodes in K. The two extreme situations are those when K contains only two nodes, the source s and the destination t, or all nodes of the graph, and they are called 2-terminal and all-terminal connectivity, respectively.

Several papers have discussed the K-terminal connectivity and its extreme problems with directed or undirected, general or special graphs, dependent or independent components (nodes or arcs), as well as the cases when only the arcs, only the nodes or both are subject to failures. Detailed overview of the papers belonging to this group can be found in [2, 7]. However, it was shown in [8] that all analysis problems relating K-terminal reliability of general graphs are at least as hard as the renowned set of NP-Complete problems. Additionally, even if the derivation of the connectivity measures is feasible, the applicability of these parameters to the description of telecommunication networks is very questionable since connectivity is not able to reflect properly the degradation of the network performance.

2.2 Maxflow (capacity) measures

In the second group of papers the initial step was made by Lee [1] who considered network reliability as the probability of successfully transmitting the required amount of information from the source node to the destination. Many other results can be referred as the extensions of this measure to general performance indices and as the development of analysis techniques applied to the derivation of these metrics. A general definition of this class of measures can be found in [9] where Rushdi interprets the previous definitions [4, 6] in terms of certain (2, K or all-terminal) mean normalized capacities in the network.

In this first application of performance indices the normalization factor is the maximum capacity, which is compared to the achievable capacity in the different network states. In the evaluation the actual routing schemes are not taken into consideration. The applied models are graphs with edge capacities and a great number of techniques have been developed for the solutions. Among these methods several cutset and composite path enumeration, as well as network decomposition techniques can be mentioned. In [2, 7, 10] many of the known methods are summarized and evaluated.

[1]Hereafter we only deal with the reliability of networks apt to random failures.

2.3 Multicommodity flow measures

In the third stage of network reliability analysis the network is considered as a system simultaneously providing transmission capacities among its endpoints. The reliability is measured by performance indices, however, the normalization factor is expressed as the sum of the realized simultaneous capacities (flows) instead of the maximum flows between the nodepairs. Due to the approach these measures are able to take into consideration the impact of the actual routing schemes (realization of capacities through the network), and in the particular failure states the applied protection and restoration techniques, as well.

This group of measures can be identified as a straightforward extension of the previous performance indices, and several practical analysis results are available dealing with the impact of network architecture and protection techniques on the reliability of communication networks. In [16] the considered reliability measure is the average satisfied fraction of the capacity demands. Different protection techniques (unprotected, transmission path diversity and 1+1 hot-standby) are compared in case of one and two-layer network architecture.

An important step to evaluate these network measures was introduced in [13] where the authors focus their attention on the extension of the usual definition of availability to network availability. In their definition a transmission network is said to be in up-state if it is available for the $g[i]$ % of the priority class i traffic, $i = 1, 2, ...N$, otherwise it is said to be in down-state. This definition is extended to priority-k network availability which is defined as the probability that the network is available to the traffic classes $1, 2, ..., k$, $k \leq N$. Naturally, the availability of traffic classes is derived by using the actual capacity requirements and the available routing schemes.

In [17] a tool is presented which can be effectively applied for the reliability analysis of layered transmission network architecture. The calculated reliability measures are based on [13] and the failure of DXC-s (digital cross-connects), cables and transmission systems as well as the restoration capabilities of the network in the different layers are taken into consideration. In the analysis different restoration algorithms are compared in case of real-size networks, and simulation technique is used for the derivation of lower bounds of reliability metrics.

These measures mean an important step in the reliability analysis of real networks, since they characterize much more the technical implementation than the capabilities of the network structure. However, the detailed description of this measures is still missing in the literature.

2.4 Performability measures

The three above measures take into account the random feature of network capacities, however, all of them disregard from the randomness of demands met by the network. Therefore, in the fourth group of papers performability measures are introduced as metrics of reliability [11, 12]. In this case the traffic routing influences significantly the performance of the network. Obviously, these measures give much more information about the degradation of service provided by the network, but the derivation of the measures needs much more details about the traffic control of the network as well.

In paper [14] the authors focus their attention on determination of the expected loss of traffic when rerouting processes are available in the network in case of failure. In the model independent failures and repairs of nodes, cables and system arcs are taken into consideration. The numerical analysis consists of two separate phases:

1. Rerouting calculation: computing the lost of traffic in a given state of the network after performing the rerouting process taking into consideration the restoration algorithm.

2. Probabilistic calculation: computing the probabilistic formulation of the expected lost of traffic and availability based on a stratified sampling technique and which provides lower and upper bounds for the investigated parameters.

3 Modelling and analysis

3.1 Basic notation

In model formulation the following quantities play a key role:

- $G = (V, E)$: graph representing the network
- V: set of nodes
- E: set of edges
- K: set of commodities, where a commodity $k \in K$ is associated to a node pair $(s_k, t_k) \in VxV$, and corresponds to a node-to-node demand with value $d(k)$ between s_k and t_k
- P: set of paths in G, where an $[u, v]$ path $p \in P$ in graph G is a sequence of consecutive nodes and edges of G containing no repetitions and connecting u and v,
- set of components: $\mathbf{C} = \{C_l\}$, each component is assigned to one node or edge, and can be assigned to one or a group of subnetworks
- state of network component C_l:

$$S(C_l) = \begin{cases} 1, & if\ the\ component\ is\ in\ up\ (failure\ free)\ state \\ 0, & if\ the\ component\ is\ in\ down\ (failed)\ state \end{cases}$$

- $\mathbf{S} = \{S_n\}$: set of the failure states of the network, a combination of the states of the components
- $\Pr(S_n)$: the probability of network state S_n.

3.2 Performance indices

The failure of network components affect the services provided by the network in several forms. Many of these effects can be formalized with the following general expressions ([9, 15]):

$$NPI = \frac{\mathbf{E}(Perf)}{Perf_{max}} = \frac{\sum_{S_n \in S} Perf(S_n) \Pr(S_n)}{Perf_{max}} \tag{1}$$

where

- NPI denotes the network performance index, the expected relative network performance
- $\mathbf{E}(Perf)$ denotes the expected value of the network performance
- $Perf_{max}$ denotes the maximum value of the network performance provided that all network components are in the up state
- $Perf(S_n)$ denotes the performance of the network in state S_n.

Equation (1) can be interpreted in a lot of manner depending on the definition of $Perf$. Some examples for the definition of $Perf(S_n)$ are as follows:

1. the connectivity of the graph representing the network in state S_n between the node pairs $s - t$
2. the available capacity in the graph representing the network in state S_n between the node pairs $s - t$
3. the available capacity in the network in state S_n between the node pairs $s - t$
4. the total throughput of the network in state S_n

3.3 Illustration

Equation (1) expresses network reliability in a very simple form, which makes it possible to determine the performance indices with the derivation of the two quantities, the state probabilities and the performance indices in each network states. In order to illustrate the derivation of these parameters let us suppose a transmission network reliability analysis as an example. The realized transmission demands are identified as follows:

- set of capacity demands: $\mathbf{D} = \{D_m\}$
- value of capacity demands m: d_m, $[d_m] = bit/sec$

and we consider only the following three simple protection possibilities:

1. Unprotected capacity demands: Only one single route is implemented between the node pairs. The realized capacity on this path is $d_{m1} = d_m$
2. Path diversity: Two routes are implemented between the node pairs. The realized capacity on these paths is $d_{m1} + d_{m2} = d_m$
3. 1+1 path protection: Two routes are implemented paths between the node pairs. The realized capacity on these paths is $d_{m1} = d_{m2} = d_m$

Without the loss of generality but in order to make the illustration simpler we suppose that maximum two routes exist. Since in the first case there is no protection while in the second and third cases it is dedicated, the reliability analysis of the transmission demands can be performed demand by demand. For each demand a simple model can be drawn as it is plotted in Figure 1, where $C_{12}(D_m)$, $C_1(D_m)$ and $C_2(D_m)$ denotes the set of components causing the failure of the capacities in both, in the first or in the second routes, respectively.

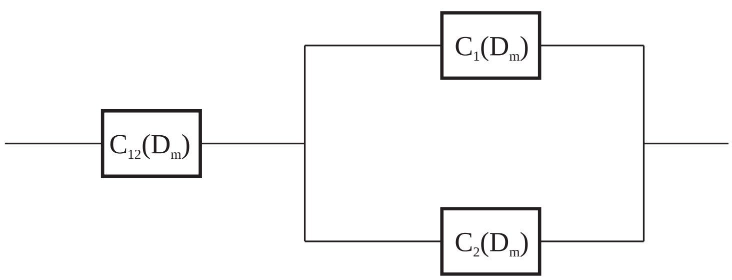

Figure 1: The simplified picture of demand routes on the graph

The network level performance index can be expressed with the expected available capacities:

$$MCR = \frac{\mathbf{E}(MC)}{CAP_{max}} = \frac{\sum_{S_n \in S} \sum_{D_m \in D} \min\left(d_{mact}(S_n), d_m\right) \Pr\left(S_n\right)}{\sum_{D_m \in D} d_m} \tag{2}$$

where

- MCR denotes the mean capacity ratio
- $\mathbf{E}(MC)$ denotes the expected value of the total capacity
- CAP_{max} denotes the maximum capacity to be realized
- $d_{mact}(S_n)$ denotes the available capacity of demand D_m in state S_n
- $\Pr\left(S_n\right)$ denotes the probability of state S_n.

In a general case, when the components are dependent, the derivation of state probabilities needs a lot of extra efforts, however, if the failure and repair of all network components can be considered independent from each other it can be expressed in a very simple manner:

$$\Pr(S_n) = \prod_{C_l \in CU(S_n)} A(C_l) \prod_{C_l \in CD(S_n)} (1 - A(C_l)) \tag{3}$$

where

- $CU(S_n)$ and $CD(S_n)$ denote the set of components being in the up or down state in network state S_n, respectively, and $CU(S_n) \cup CD(S_n) = C$, $CU(S_n) \cap CD(S_n) = \emptyset$
- $A(C_l)$ is the availability of component C_l which can be written as:

$$A(C_l) = \Pr(S(C_l) = 1) = \frac{1/\lambda(C_l)}{1/\lambda(C_l) + MDT(C_l)} = \frac{1}{1 + \lambda(C_l)MDT(C_l)} \tag{4}$$

  where

  - $\lambda(C_l)$: the failure rate of component C_l, $[\lambda(C_l)] = 1/hour$
  - $MDT(C_l)$: the mean down time of component C_l, $[MDT(C_l)] = hour$.

The actual capacity d_{mact} in Equation (2)depends on the failed components in the given state and on the applied protection and varies between 0 and 2 d_m. The derivation is relatively simple if the transmission routes are given [23].

3.4 Critical issues in reliability modelling and analysis

Concerning the illustration two groups of problems can be identified. The first problem is independent from the applied protection it comes directly from the extremely large number of network states and from the dependence of the components. The number of states can be reduced by assigning only one component to each node and arc. This assignment is practical because it can reduce the dependence of the components as well, however, due to the great number of nodes and arcs, even in this case no chance to investigate all network states.

The second group of problems comes from the fact that the above network model does not describes precisely the effect of failures. In the illustration the problem is that many of the components on a route does not cause the drop-out of the entire capacity or if only one component is assigned to each node or arc the model does not express the difference between the effect of different failures of a given node or arc. This is a very critical problem since in many cases the goal of network planning, management and control or equipment design is to eliminate or at least to reduce the impact of failures on the performance measures [19].

Therefore, if the modeller merges the components into arcs or nodes the model is not able to express precisely the effect of the applied resilience or if he distinguishes them the analysis is not tractable. In the remaining part of the paper, first, we show the usually used approximation techniques which can reduce the problems originating from the great number of states, and then we present a method which can lead to an adequate and tractable model even in more complicated, multilayer network environments.

3.5 Lower and upper bounds

In order to reduce the computational efforts one of the most widely used approach is published by Li and Silvester [5]. They provided that the network is completely break-down or operational in the states which are not taken into account in the accurate analysis. Based on this assumption, they introduced lower and upper bounds, respectively[2].

[2]One of the newest achievements is derived by Strayer and Colbourn in [18] where they provide bounds for probabilistic distances of weighted bidirectional graphs, and extend the results to bound probabilistic maxflow and mean maxflow. The results obtained by their method compare favorably with other known bounds.

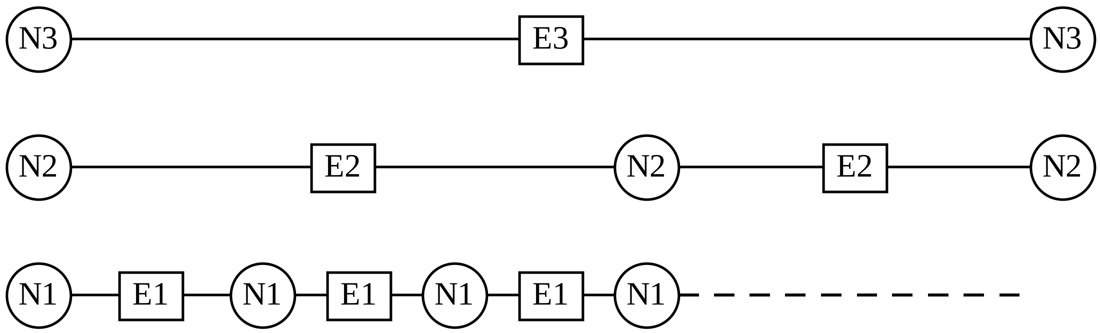

Figure 2: The elements of the network reliability model

Following [5], Equation (1) provides a possibility for the definition of lower and upper bounds of the performance indexes since one can divide the states of the space into two subsets. Let us denote these subsets S_0 and S_c. Using this notation the lower bound of NPI can be expressed as

$$\begin{aligned} NPI_{min} &= \frac{\sum_{S_n \in S_0} Perf(S_n) \Pr(S_n)}{Perf_{max}} + \frac{\sum_{S_n \in S_c} Perf_{min} \Pr(S_n)}{Perf_{max}} \\ &= \frac{\sum_{S_n \in S_0} Perf(S_n) \Pr(S_n)}{Perf_{max}} \end{aligned} \tag{5}$$

where $Perf_{min}$ can be estimated by 0. The upper bound can be written as

$$\begin{aligned} NPI_{max} &= \frac{\sum_{S_n \in S_0} Perf(S_n) \Pr(S_n)}{Perf_{max}} + \frac{\sum_{S_n \in S_c} Perf_{max} \Pr(S_n)}{Perf_{max}} \\ &= NPI_{min} + \sum_{S_n \in S_c} \Pr(S_n) \end{aligned} \tag{6}$$

The difference between Equations (5) and (6) is the total probability of the states belonging to subset S_c. Therefore if one can determine the most likely states, the less probable states can be neglected from the analysis. Defining the set of most and less probable states as S_0 and S_c respectively, the performance analysis can be focused on S_0 and the accuracy of the evaluation can be controlled by the total probability of the states in S_c.

4 Multilayer modelling and analysis

4.1 Multilayer network model

In order to build up network reliability models which are able to take into consideration the multilayer structure of communication networks and the possible multilayer protection techniques we propose a multilayer network reliability model. In the model in each layer components are assigned to the nodes and arcs corresponding to the equipment realizing the switching or cross-connecting and the transmission (connection) functions in the given layer, respectively.

In Figure 2 the main elements of the model are illustrated with a simplified, three layer model. The three layers can correspond to the physical (1), one of the multiplex (2) and the transmission capacity demand layers (3), respectively. Each layer can be described by a graph with nodes (N1, N2, N3) and arcs (E1, E2, E3). The reliability parameters (failure rates and repair times) of the network elements are supposed to be independent of each other and therefore, the availability of the components can be calculated from Equation (4) [23]. Nevertheless, the lower layers have a common impact on all the above layers, and they can describe certain dependencies among the layers. The lower and upper bounds can be expressed in the usual manner, but furthermore, the multi-layer reliability model makes it also possible to introduce new bounds to the measures by neglecting layers or by merging them together.

4.2 Numerical results

In the case study the investigated network is a real size nationwide optical network with more than 70 nodes, and more than 80 links. The geographical extension of the network is about 500 km x 200 km. The applied transmission technology is SDH, the network architecture is two-level; on the lower level 8 ring subnetworks and on the upper level a mesh subnetwork. The interconnection of the rings are dual-homed [20].

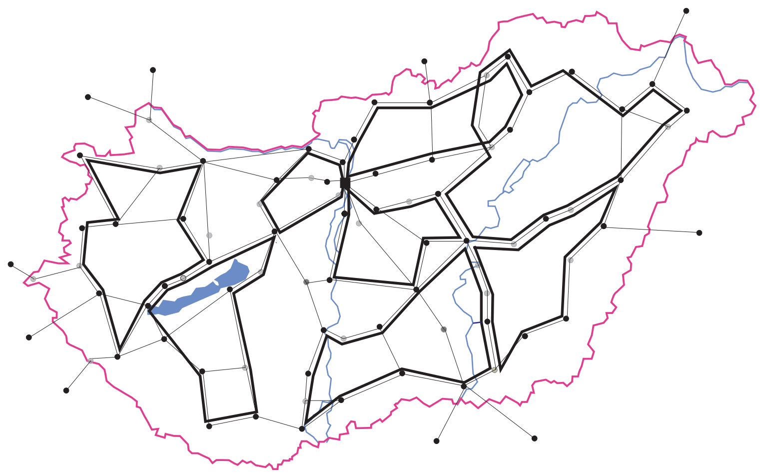

Figure 3: The graph of a hypothetical optical nationwide network

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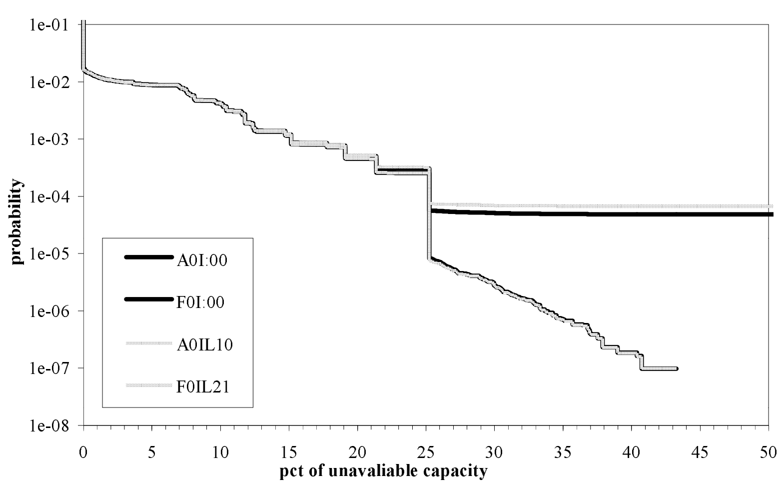

Figure 4: Probability of unavailable capacity versus the unavailable capacity ratio

In Figure 4 the probability of unavailable capacity is plotted. The solid lines show the upper and lower bounds calculated with the usual [5] estimation when 20000 states were taken in account. The slightly wrong curves depicted with dotted lines present the same bounds of 5000 states when the multilayer model is used for pessimistic merging or optimistic eliminating the less important components of the network (effecting only the VC12 and VC3 connections of the network). The results are very close to are very close to the ones taking all components in consideration.

5 Conclusions

In the paper some questions concerning the reliability analysis of communication networks are summarized. The basic unilayer approach is presented and a possible extension for multilayer modelling is described. Both modelling approaches has been implemented at Technical University of Budapest and a limited multilayer solution has been applied at the Hungarian Telecommunication Company Ltd [23, 24] for the SDH core network and it has been also used in the availability analysis of optical networks. Some of the achievements in the frame of the EURESCOM P615 project are presented in [22, 25, 26].

The multilayer extension introduced in the second part of the paper is very promising. The first results show that the generic structure makes it possible to model the multilayer structure as well as several multilayer protection techniques, while on the other hand, efficient lower and upper bounds can be automatically derived based on the model.

The ongoing development activities aim at the implementation of the described modelling technique in the network planning software applied at the Hungarian Telecommunication Company and the extension of the method toward traffic layers and more complex restoration techniques. One of the objectives of these developments is to prepare the analysis of ATM networks with combined multilayer ATM-SDH resilience [21].

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