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Availability analysis of multi-layer optical networks

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ABSTRACT

In networks around the globe, traffic volumes are swelling and capacity demand is tremendously growing. To meet large capacity needs WDM optical networks are being introduced by numerous network operators. The high traffic concentration on network elements increases the risk and the potential impact of failures. Due to the increasing traffic aggregation and high value services resilience is of basic importance in the high capacity WDM transport networks.

In order to evaluate the different resilience options the network availability should be calculated. The state space of availability models for real size networks is tremendously large, thus, statistical sampling methods should be applied.

On the other hand, multi-layer protection schemes implemented in real networks result in fast and effective recovery from single failures. Therefore, there is a large number of network failure states with relatively high probability and without capacity or performance degradation that has significant impact on the applicability and efficiency of the statistical analysis methods.

The paper provides a simple reliability model for multi-layer SONET/SDH over WDM networks, demonstrates the application of stratified sampling in network reliability analysis, and compares the efficiency of methods based on deterministic bounds, Monte Carlo simulation and stratified sampling in case of multi-layer optical networks with different protection schemes.

1 Introduction

The introduction of wide-band services and the "Internet-revolution" results in a transmission capacity demand explosion in transport networks. Since there is a huge amount of fiber in the networks it is obvious that the network operators are highly interested in exploiting this potential. Wavelength division multiplexing (WDM) technique has been recognized as the key technology to upgrade fiber plants in existing optical networks. Due to the fast progress in optical technology WDM multiplex systems with tens of optical channels are commercially available, and systems with more then hundred wavelengths are foreseen in the near future.

Because of the huge capacity of WDM systems the impact of failures has become more important. In order to reduce the effect of failures, based on the more and

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more complex networking functionality realized in the optical domain the protection and restoration schemes well known from SONET/SDH networks can be implemented in the optical network layer, as well.

- In case of 1 + 1 dedicated protection the information is permanently transmitted via two node or edge disjoint transmission routes. Based on the monitoring of the received signals the receiver end performs path selection, i.e. in case of signal degradation it switches over between the received signal flows.
- In case of shared protection working and protection entities are distinguished and particular working entities that are not subject to common failures share some protection resources. In this case the switching action should be performed in both ends of the connections, and it requires synchronized timing.
- Dedicated and shared protection is point-to-point related resilience mechanisms, while restoration is a network level technique implementing resilience more efficiently. In case of restoration the spare resources are shared, since they are applied to recover the network from different failure states and the management system reacts the failure events by rearranging the failed transmission routes with the help of configurable cross-connect nodes. Partial or end-to-end reconfiguration of the failed routes can be performed according to the policy implemented in the management system. However, the network complexity is higher since nodes with flexibility and intelligence as well as complex management system are required to implement restoration.

A vast number of publications are available in the literature covering the application of protection and restoration architecture and techniques in mesh (e.g. [1]) and in shared protection ring (e.g. [2]) WDM networks, as well as the extension of MPLS recovery techniques to the optical domain (MPλS) [3]. [4] summarizes some proposals concerning the improvement of the availability of the studied optical architecture.

Due to the gradual development in current networks several transport technologies (IP, ATM, SONET/SDH, WDM) co-exist in complex multi-layer architecture, where some of the layers can provide protection and/or restoration options. Good overviews of general multi-layer protection strategies and some related dimensioning methodologies have been published in [5], [6], and [7].

The majority of publications on availability analysis focused on the results and not on the methods applied in the analysis (e.g. [4, 8, 9]). There are only a few publications covering the modeling aspects, like the functional modeling based serial-parallel description of WDM networks [10], the two-terminal and all-terminal models for WDM rings [11].

The availability of an unprotected network is dominated by the single failure states, but in case of well-protected networks the applied protection schemes recover the network at least from any single failure cases, therefore, the dominant failure configurations are the multiple failure ones [12]. For small networks the probability of multiple failures is small, and the availability can be easily calculated. However, if the network contains elements in the order of thousands, the accumulated probability of multiple failures becomes significantly higher, the availability analysis of networks with some technological layers and with resilience schemes implemented in different layers becomes much more complex and therefore, sophisticated modeling and analysis methods are required.

The objective of the paper is twofold. On the one hand, the multi-layer model of different resilience schemes is given, and on the other hand, more emphasis is given to the applicability of different availability analysis techniques in case of different complex network resilience options.

The paper is organized as follows. Section 2 provides the simplified functional models of equipment used in SONET/SDH over WDM multi-layer network architecture, describes the corresponding reliability models, and highlights the reliability analysis measures based on performance indices. Section 3 describes the basic statistical methods that can be applied in reliability analysis with main emphasis on stratified sampling and then Section 4 gives a comparison of the different resilience options. Finally, Section 5 concludes the paper.

2 Reliability Modeling of Multi-Layer Optical Networks

2.1 Multi-layer network model

The network under study is a SONET/SDH over WDM structure. The fundamental networking functions, routing and protection are implemented in both technological layers. The SONET/SDH layer is applied to aggregate traffic from limited size network regions and has a two level hierarchy: rings on the lower level and a mesh on the upper level with dual-homing interconnections (i.e. each ring is connected to the mesh via two nodes). The transmission routing is hierarchical, only the mesh is allowed to transit demands between two, not neighboring rings. The SONET/SDH layer supports add-drop multiplexing, local cross-connecting and protection switching in the higher order path level. The applied SONET systems are STS-48 (SDH STM-16) ADMs in the rings and STS-48 line systems in the mesh.

The WDM mesh is applied as a server layer for the STS-48 client signals of the SONET mesh and for the optical traffic directly launched to the network in the mesh nodes. Terminal multiplexing and protection switching in the optical channel level are implemented in the WDM layer.

The structure of the ring and mesh nodes is illustrated in Figures 1 and 2. Ring nodes are equipped with SONET functionality only, however, mesh nodes include

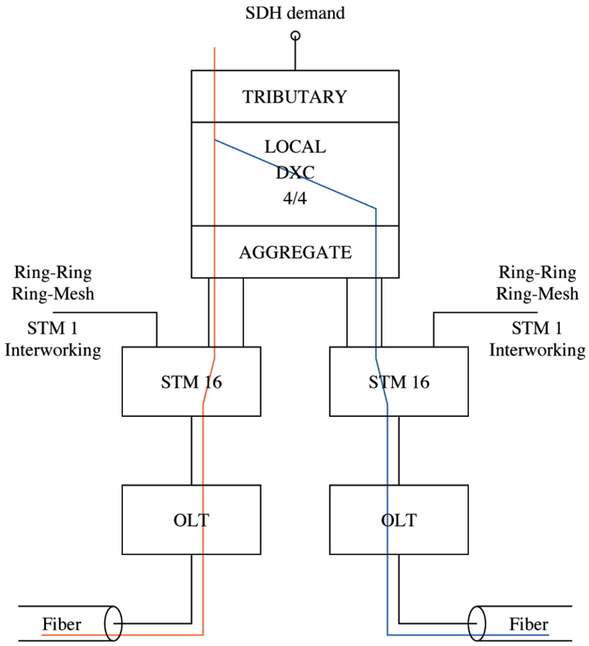

Figure 1: Structural scheme of a SONET Ring Node.

both SONET/SDH and WDM capabilities. The detailed structure of a ring node is shown in Figure 1. The node is realized by a general STS-48 SONET add-drop multiplexing structure, which supports OC-3 (SDH VC-4) level transmission demands and the same level interworking. The local cross-connect (LDXC 4/4) supports OC-3 level flexibility and implements the higher order path sub-network connection protection (HOP SNCP) in OC-3 level.

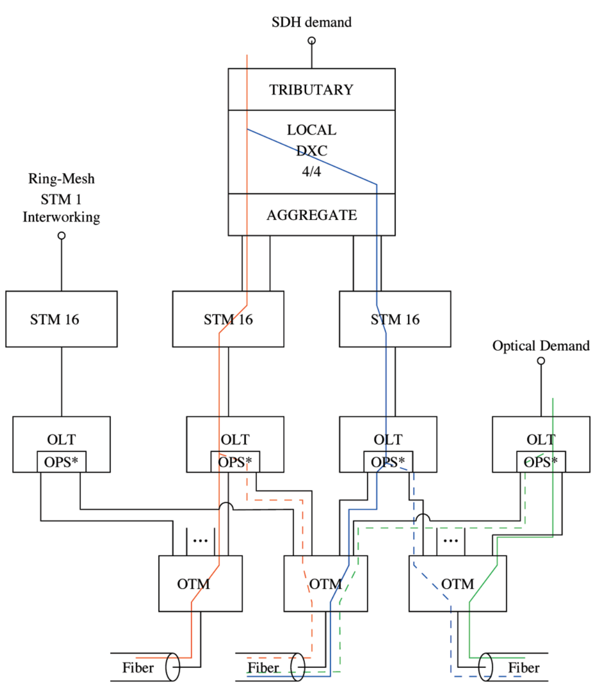

Figure 2: Structural scheme of a Mesh Node.

The detailed structure of a mesh node is given in Figure 2. The SONET part of the node realized with SONET cross-connect consists of switching backplane supporting OC-3 level flexibility and implements the higher order path sub-network connection protection (HOP SNCP) in OC-3 level, STS-48 line multiplexer unit and optical line termiations (OLT). OLTs are connected to optical terminal multiplexers (OTM) via optical protection switching (OPS) functionalities (if required) to support 1 + 1 optical channel dedicated protection in the WDM layer.

The optical demands are launched to the optical line terminations (OLTs) via OPS. Based on this feature 1 + 1 optical channel protection can be applied to optical demands. The similar SONET and WDM protection schemes enable to use similar functional models for all sets of transmission demands from availability point of view.

The above network configuration supports different options for the realization of the transmission capacity demands launched into the network both in OC-3 level and grouped into STS-48 bundles or launched into the networks as optical channels. Different path oriented protection options are illustrated in Figures 1 and 2. Unprotected OC-3 SONET path originates from the tributary side of the SONET cross-connect, routed via different network components and launched to a fiber (solid red line). To apply OC-3 level 1 + 1 path protection, electrical protection switching (EPS) functionality implemented in the cross-connect backplane is required (solid red and blue lines depict the dedicated 1 + 1 OC-3 level protection path).

To support SONET demands with 1 + 1 dedicated optical channel protection implemented in the WDM layer, optical protection switching functionality is required. In Figure 2 the optical protection is applied both to the working (solid red) and protection (solid blue) SONET path (dashed lines with corresponding color represent the WDM protection of SONET demands). Finally, to protect native WDM demands (working route with solid green line) the same optical protection switching functionality is applied, and the protection path is launched to disjointly routed fiber (dashed green line).

Based on the above node models different demands can be realized without protection or with 1 + 1 dedicated single and multi-layer protection schemes.

2.2 Definition of performance index

The size of the state space generated by the failure states of the nodes and links of a real size network makes the reliability modeling, analysis and design problem very complex. Several approaches have been developed, and many papers have been devoted to these issues. The main groups of measures introduced for the description of network reliability can be summarized as follows[1]:

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

A simple performance index defined as the ratio of the performance in a given state to the maximum performance provided by the network can be formalized as follows:

$$NPI = \frac{\sum_{y \in Y} Perf(\mathbf{y}) p(\mathbf{y})}{Perf_{max}} \tag{1}$$

where the notation of

- NPI: the network performance index
- **y:** state of the network (definition is given later)
- $p(\mathbf{y})$: probability of state $\mathbf{y}$
- $Perf(\mathbf{y})$: network performance in state $\mathbf{y}$
- $Perf_{max}$: maximum network performance (in the ideal state).

This formalization enables to express the connectivity, maxflow and multicommodity flow measures as well, and furthermore, it provides a framework to generate more complex reliability measures.

2.3 Basic notation of reliability analysis

In order to formulate the problem, let us assume that the following quantities are given

- the number of elements in the network K
- the probability of malfunction of element i denoted by p_i, $i = 1, \ldots, K$
- a functionality vector:

$$\mathbf{y} = (y_1, \ldots, y_K)$$

where

$$y_i = \begin{cases} 0 \text{ if element } i \text{ is operational} \\ 1 \text{ if element } i \text{ is malfunctioning} \end{cases}$$

$$y \in Y = \{0,1\}^K$$

- a measure of loss $g: Y \to R$, where

$$g(\mathbf{y}) = 1 - \frac{Perf(\mathbf{y})}{Perf_{max}} \tag{2}$$

expresses the loss of system performance due to a failure scenario represented by vector **y.**

The two main reliability measures are defined as follows:

1. *Average Loss* (AL) expressed as

$$\mathbf{E}(g(\mathbf{y})) = \sum_{y \in Y} g(\mathbf{y}) p(\mathbf{y}) \tag{3}$$

An example for the application of this measure is the loss of traffic, when the randomness of demands met by the network is taken into account [14], and the performance indices are determined with the consideration of the complex rerouting or/and restoration capabilities introduced in the network.

2. the *Network Unavailability (or outage)* (NU)

$$P(g(\mathbf{y}) > C) = \sum_{\mathbf{y}: g(\mathbf{y}) > C} p(\mathbf{y}) \tag{4}$$

As an example in [15] the authors extend the usual definition of availability to network availability. In their definition a transmission network is considered to be in up-state if it is available at least for the g% of the traffic, otherwise it is in down-state.

In this paper we focus our attention on the determination of the first measure AL in case of some multi-layer optical networking applications.

2.4 Computational aspects of reliability analysis

Equations 3 and 4 clearly indicate the critical issues of network reliability analysis, since both expressions comprise the enumeration of all states, the calculation of $p(\mathbf{y})$ for each state and the derivation of $g(\mathbf{y})$ for each state.

The determination of state probabilities is simple if the network elements can be considered independent since the Down Time Ratio (DTR) can be defined for each component as

$$DTR_i = p_i = \frac{MDT_i}{1/\lambda_i + MDT_i} = \frac{\lambda_i MDT_i}{1 + \lambda_i MDT_i} \tag{5}$$

where λ_i and MDT_i denote the failure rate and the Mean Down (Repair) Time of component i, respectively [16], and any state probability $p(\mathbf{y})$ can be written as

$$p(\mathbf{y}) = \prod_{i:y_i=0} (1 - DTR_i) \prod_{j:yj=1} DTR_j \tag{6}$$

Although in case of complex resilience schemes the calculation of the performance index requires "network redesign" or "network performance analysis" in each network state, the application of unprotected connections or 1 + 1 protection schemes makes it possible to build up very simple structural reliability model as it is depicted in Figure 3:

In Figure 3 all blocks correspond a group of network components. If a connection is unprotected only block 1–2 exists and it comprises all network components tak-

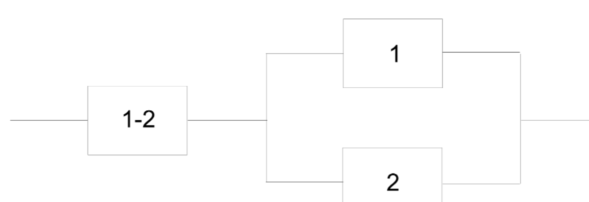

Figure 3: The simplified reliability model of connections.

[1] *In [13] a more detailed overview of the definitions used in network reliability analysis is given.*

ing part in the realization of the given connection and from reliability point of view they form a series system. If the connection is protected all components taking part in both routes belong to block 1–2, while the components taking part only in one of the routes belong either block 1 or 2.

In any failure state for each connection this simple graph model is evaluated and the provision of the connection demand is considered failed if either any of the components in block 1-2 failed or at the same time, at least 1 component in block 1 and 2 failed. The failure of a connection increases the capacity loss in the network.

In order to measure the efficiency of a given algorithm we introduce the following indices:

Mean Square Error (MSE):

$$E(\eta - AL)^2 \tag{7}$$

if η is a statistical estimate (the sample set $\{\mathbf{y}_1, \ldots, \mathbf{y}_N\}$ is drawn randomly).

Squared Error (SE):

$$(\eta - AL)^2 \tag{8}$$

if η is a deterministic estimate (the sample set $\{\mathbf{y}_1, \ldots, \mathbf{y}_N\}$ is drawn according to some deterministic rule).

3 Basic Statistical Methods in Reliability Analysis

3.1 Monte Carlo method

One of the classical statistical methods in reliability analysis is the Monte Carlo (MC) method. According to this method a sequence $\mathbf{y}_i$, $i = 1, \ldots, N$ of samples are drawn subject to the underlying distribution $p(\mathbf{y})$.

The basic steps are identified as follows:

1. Generate a pseudo-random number in the interval [0, 1);
2. Determination of state $\mathbf{y}$ by transformation from uniform distribution to the required $p(\mathbf{y})$
3. Determination of $g(\mathbf{y})$ for the given network
4. Calculation of the mean for $g(\mathbf{y})$:

$$E(g(\mathbf{y})) \approx \frac{1}{N}\sum_{i=1}^{N} g(\mathbf{y}_i), \tag{9}$$

The shortcomings of the Monte Carlo method are well known since only the following accuracy can be achieved:

$$E(\eta - E(g(\mathbf{y})))^2 = \frac{Var(\mathbf{y})}{N}, \tag{10}$$

which yields only an $O\left(\frac{1}{N}\right)$, therefore rather slow, convergence.

3.2 Reliability analysis using deterministic bounds

In order to reduce the computational efforts there is a well-know approach published by Li and Silvester [17]. Based on their approach Equation (1) provides a possibility for the definition of lower and upper bounds for the performance indices since one can divide the states of the space into two subsets. Let us denote these subsets $\mathbf{Y}_0$ and $\mathbf{Y}_c$. Using this notation the lower bound of NPI can be expressed as

$$\begin{aligned} NPI_{min} &= \frac{\sum_{\mathbf{y}\in \mathbf{Y}_0} Per\, f(\mathbf{y})p(\mathbf{y})}{Per\, f_{max}} + \frac{\sum_{\mathbf{y}\in \mathbf{Y}_c} Per\, f_{min}\, p(\mathbf{y})}{Per\, f_{max}} \\ &= \frac{\sum_{\mathbf{y}\in \mathbf{Y}_0} Per\, f(\mathbf{y})p(\mathbf{y})}{Per\, f_{max}} \end{aligned} \tag{11}$$

if the minimum performance $Per\, f_{min}$ can be estimated by 0. The upper bound can be written as

$$\begin{aligned} NPI_{max} &= \frac{\sum_{\mathbf{y}\in \mathbf{Y}_0} Per\, f(\mathbf{y})p(\mathbf{y})}{Per\, f_{max}} + \frac{\sum_{\mathbf{y}\in \mathbf{Y}_c} Per\, f_{max}\, p(\mathbf{y})}{Per\, f_{max}} \\ &= NPI_{min} + \sum_{\mathbf{y}\in \mathbf{Y}_c} p(\mathbf{y}) \end{aligned} \tag{12}$$

Therefore, if one determine the most likely states as $\mathbf{Y}_0$ and the less probable states as $\mathbf{Y}_c$, the states of $\mathbf{Y}_c$ can be neglected from the analysis, the performance analysis can be focused on $\mathbf{Y}_0$ and the accuracy of the evaluation can be controlled by the total probability of the states in subset $\mathbf{Y}_c$.

3.3 Stratified sampling

In this section we describe an approach to accelerate the Monte Carlo simulations, suggested in [18]. The method called stratified sampling ([19]) is based on grouping the samples into different classes. The additional notation can be introduced as follows:

- partition $y = \{Y_i\, i = 1, \ldots, L\}$ $Y = \cup_{i=1}^{L} Y_i$ and $Y_i \cap Y_j = \theta$ of the states
- the probability of being in class $i \rightarrow P_i = \sum_{\mathbf{y}\in Y_i} p(\mathbf{y})$;
- the average loss expressed in a structured form

$$\mathbf{E}(g(\mathbf{y})) = \sum_{i=1}^{L} P_i \mathbf{E}(g(\mathbf{y}) \mid \mathbf{y} \in Y_i) = \sum_{i=1}^{L} P_i m_i$$

- a sampling allocation $(N_1, N_2, \ldots, N_L)$ $\sum_{i=1}^{L} N_i = N$
- an estimation of the conditional expected value m_i

$$m_i \approx \frac{1}{N_i}\sum_{k=1}^{N_i} g(\mathbf{y}_k^{(i)})$$

  where $\mathbf{y}_k^{(i)}$ is the kth sample drawn from class i
- the overall estimation

$$\eta := \sum_{i=1}^{L} P_i \frac{1}{N_i}\sum_{k=1}^{N_i} g(\mathbf{y}_k^{(i)}). \tag{13}$$

In the sequel four basic properties of stratified sampling are summarized[2]:

[2] *The attention of readers interested in the topic in more details is drawn to [19,20] where the proofs of these expressions are given.*

1. If the partition $y = \{Y_i\}$ of the state space and the total number of samples N is given the optimal sample allocation among the classes is defined as

$$N_{iopt} = N \frac{P_i \sigma_i}{\sum_{j=1}^{L} P_j \sigma_j} \tag{14}$$

where σ_i denotes the conditional standard deviation.
2. The standard deviation of an experience with N samples drawn according to the optimal sample allocation is written as

$$\sigma_{experiment} = \frac{\sum_{j=1}^{L} P_j \sigma_j}{\sqrt{N}} \tag{15}$$

3. The gain of stratified sampling compared to the Monte Carlo method can be written as

$$\frac{\sum_{i=1}^{L} P_i \sigma_i^2 + \sum_{i=1}^{L} P_i (m - m_i)^2}{(\sum_{i=1}^{L} P_i \sigma_i)^2} \geq 1 + \frac{\sum_{i=1}^{L} P_i (m - m_i)^2}{(\sum_{i=1}^{L} P_i \sigma_i)^2} \tag{16}$$

4. Stratified sampling still outdo Monte Carlo, if the sample allocation is done according to $N_i = NP_i$. In this case the obtained gain is proportional with $\sum_{i=1}^{L} P_i (m - m_i)^2$.

3.4 Application of stratified sampling for network reliability analysis

It can be realized from the above expressions that the efficiency of stratified sampling depends on the chosen classes, i.e. the smaller the conditional standard deviations are and the larger the differences between the expected value and the conditional expected values are, the better the estimation. In network reliability analysis the given number of failures can be a characteristic parameter that yields similar network degradation (similar conditional expected values and small conditional standard deviations). Therefore, we can introduce the following notation:

- groups of network components (i.e., cables, switches, . . . etc.) $j = 1, \ldots, M$
- the number of elements in each group $K_1, K_2, \ldots, K_M$
- the probability of the malfunction of element i from group j denoted by p_{ji}
- the generalized functionality vector

$$\mathbf{y} = (\mathbf{y}^{(1)}, \mathbf{y}^{(2)}, \ldots, \mathbf{y}^{(M)})$$

and a class can be defined as containing a given number of failed elements from each group of elements. (e.g. 1 failed cable; 1 failed cable and 1 given type of equipment; 2 failed cable; etc.)

The critical issue in the application of stratified sampling is the need of the knowledge of the class probabilities and the conditional standard deviations. The first task can be solved easily (see [18]) but the determination of the conditional standard deviations is not simple. In [20] some methods are discussed, here only one of the possible algorithms is introduced.

3.5 Algorithm "Pre-screening, post-sampling"

The experiment is divided into two phases. In the first phase only the conditional variances of the classes is estimated, while in the second phase, using the estimated standard deviations obtained in the first phase, the stratified sampling is carried out.

1. **Pre-screening phase:** $N = N_{pre} + N_{post}$
2. take $N_{ipre} := P_i N_{pre}$ samples from each class i
3. calculate the empirical variances as

$$(\gamma_i)^2 := \frac{1}{N_{ipre} - 1} \sum_{k=1}^{N_{ipre}} \left(g(\mathbf{y}_k^{(i)}) - \frac{1}{N_{ipre}} \sum_{j=1}^{N_{ipre}} g(\mathbf{y}_j^{(i)}) \right)^2$$

4. **Post-sampling phase:** set $N_{ipost} := N_{post} \dfrac{\gamma_i P_i}{\sum_{j=1}^{L} \gamma_j P_j}$
5. take N_{ipost} samples from each class i
6. perform the estimation of the expected value according to the stratified sampling principle

$$\eta := \sum_{i=1}^{L} P_i \frac{1}{N_{ipost}} \sum_{k=1}^{N_{ipost}} g(\mathbf{y}_k^{(i)})$$

4 Case Studies

The case studies presented in this section compare the efficiency of some reliability analysis methods and demonstrate the applicability of the stratified sampling in case of different resilience schemes[3].

4.1 Network to be analyzed

The network under investigation is a SONET/SDH over WDM architecture introduced in Section 2 and it can be considered as a hypothetical Hungarian backbone. The network has 50 nodes and more than 60 optical links. All nodes but one contain SONET equipment. The structure of the SONET network is hierarchical. In the lower level there are six rings aggregating traffic from smaller nodes. The rings are connected to the upper mesh level by at least two HUB nodes. The SONET mesh contains only the 9 HUB nodes.

The WDM layer of the network consists of 19 nodes. The structure of the WDM network is a flat mesh, and its topology is similar to the SONET one. The topology of the network is depicted in Figure 4.

The broadband network is divided into six regions that are realized by the corresponding SONET rings. Intra-ring SONET demands are not investigated since

[3] *The readers interested in further details concerning the statistical methods are advised to turn to [15,20], where many results concerning the main characteristics of Li-Silvester bounds and stratified sampling have been made available.*

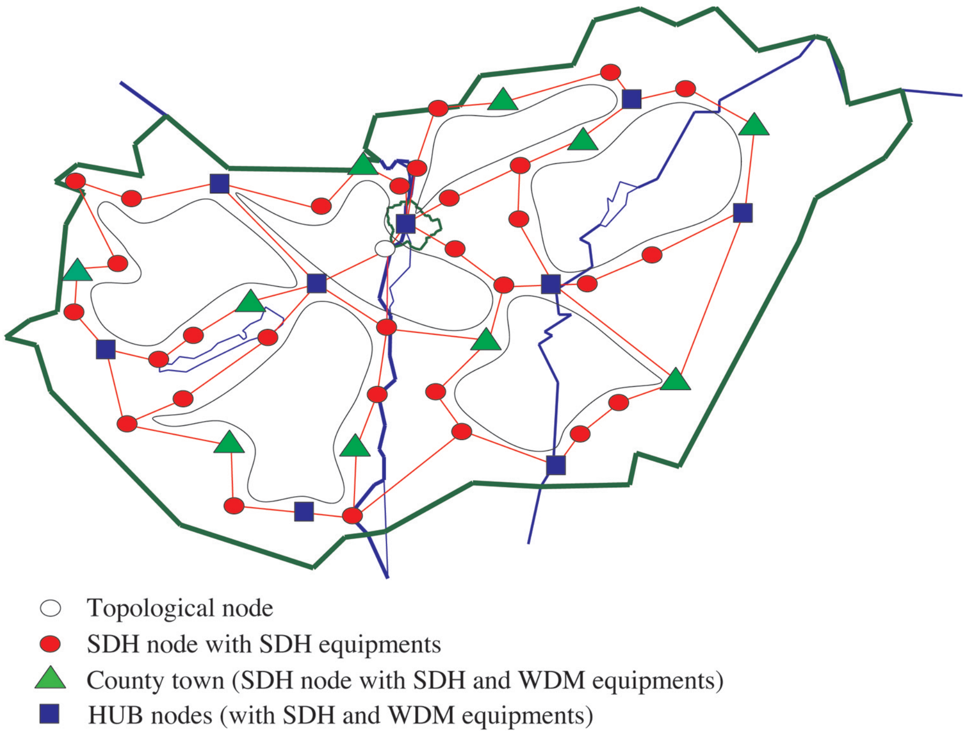

Figure 4: The topology of the investigated network.

they are not relevant for the WDM network. Two kinds of SONET demands are taken into consideration. Direct connection between two SONET nodes is allowed only if they are located in two neighboring areas (rings). The capacity of these demands is selected randomly between 1 and 4 STS-3s. Other inter-area SONET demands are routed through SONET HUB nodes. Since intra-ring traffic is not studied, these demands are modeled only in the upper level as inter-HUB connection. Their capacity is randomly selected between 1 and 4 STS-48s.

The optical network consists of county towns (filled triangle) and SONET HUB nodes (filled square). In the optical network direct connections are allowed between every optical node pair. Their capacity is randomly selected with the value of 1 or 2. The smaller traffic is routed through HUB nodes where they are bundled. Therefore, there are 1 or 2 wavelengths (randomly) between every county town and the two nearest HUB nodes. The capacity of aggregated traffic among HUB nodes is selected randomly between 1 and 4 wavelengths.

4.2 Protection options

The generic node structures applied in the case study network support different protection options for the realized transmission capacity demands. There are two sets of demands (SONET and optical) studied under different protection options, which resulted in three different cases:

1. **Unprotected network:** SONET and optical demands are protected neither in the SONET nor in the WDM layer. All demands are routed via the shortest path. This option is included in the case study only for reference purposes.
2. **Native layer protection:** SONET demands are protected by higher order path sub-network connection protection in the SONET layer both in the rings and in the mesh SONET network. This option realizes 1 + 1 OC-3 level end-to-end path protection on the whole SONET network layer (supported by the dual-homing interconnections of the SONET rings and the SONET mesh). Optical demands launched to the network in the mesh nodes are protected by 1 + 1 dedicated optical channel protection.
3. **Multi-layer protection:** SONET demands protected by higher order path sub-network connection protection in the SONET layer both in the rings and in the mesh SONET network, and in addition, STS-48 point-to-point mesh systems as well as the native optical demands are protected by 1 + 1 OCh protection in the WDM server layer.

4.3 Reliability model

The reliability model applied in the numerical studies is discussed in Section 2. Each component is independent of any other components considering either the event of failures or the repairs.

Table 1 shows the number ("Number") of the different network components in the investigated examples. Due to the assumption of statistical independence, the

Equipment	DTR	Number
LDXC	$1.6 \cdot 10^{-5}$	49
STS 48	$8.4 \cdot 10^{-6}$	462 … 869
OLT	$3 \cdot 10^{-5}$	856 … 1348
OPS	$6 \cdot 10^{-6}$	0 … 794
OTM	$1.2 \cdot 10^{-6}$	95 … 228
Fiber (per km)	$1.32 \cdot 10^{-5}$	61
Node Total	$1 \cdot 10^{-8}$	50

Table 1: DTR and number of each equipment.

state probabilities of the network can be derived easily if the DTRs (Down Time Ratio) of the components are known [13]. The data used in the reliability analysis are given in Table 1. Since the DTR of the optical fibers is length-dependent and given for 1 km the values vary between $5.28 \cdot 10^{-5}$ (4 km) and $1.468 \cdot 10^{-3}$ (110.8 km). The average length of fibers is around 40 km with its DTR of $5.28 \cdot 10^{-4}$.

The network reliability model can be easily obtained by using the multi-layer model applied in the network dimensioning phase since both the path of the demands as well as the traversed equipment in a particular layer can be directly derived by using the network dimensioning and reliability analysis tool described in [21].

4.4 Numerical results

Since the total number of components is in the order of 2 500 (1 576 ... 3 399), the number of states with two failures is around 3 000 000, and with three failures is about $2.4 \cdot 10^9$. It is obvious that only a small fraction of the state space can be sampled.

In the forthcoming analysis the efficiency of the following methods are investigated:

- the Monte Carlo (MC) and
- the Stratified Sampling with pre-screening post-sampling (PPSS).

Although the statistical methods are unbiased, i.e. the theoretical average value of the estimation equals the real value of the estimated parameter, the results of the individual experiments statistically differ. Therefore, each method for each different sample sizes (100, 1 000, 10 000) was repeated 10 times[4]. The average, the minimum and the maximum of the estimated values were derived and in order to compare the runs the mean square errors, and the variance of the estimations were calculated. The deterministic bounds of Li-Silvester method (LS) with the same sample sizes are also obtained. The average and the mean square error show the accuracy of the estimation. The minimum value, maximum value and the variance show the efficiency of the estimation.

In Figures 5-7 the results (the averages and the standard deviations) are normalized. The reference value in each figure is obtained with 10 000 samples of PPSS. All figures are divided into two parts. In the upper part the real value of the investigated performance index (expected loss of demands) is plotted, while in the lower part of the figure shows the normalized standard deviation to the real value for the statistical methods and the difference between the upper and lower bounds for the LS method. In these figures both parameters are plotted in logarithmic scale.

As it can be seen from Figure 5, for small sample size all statistical methods provide satisfactory accuracy. How-

[4] *In any cases from the ideal state only 1 sample was taken.*

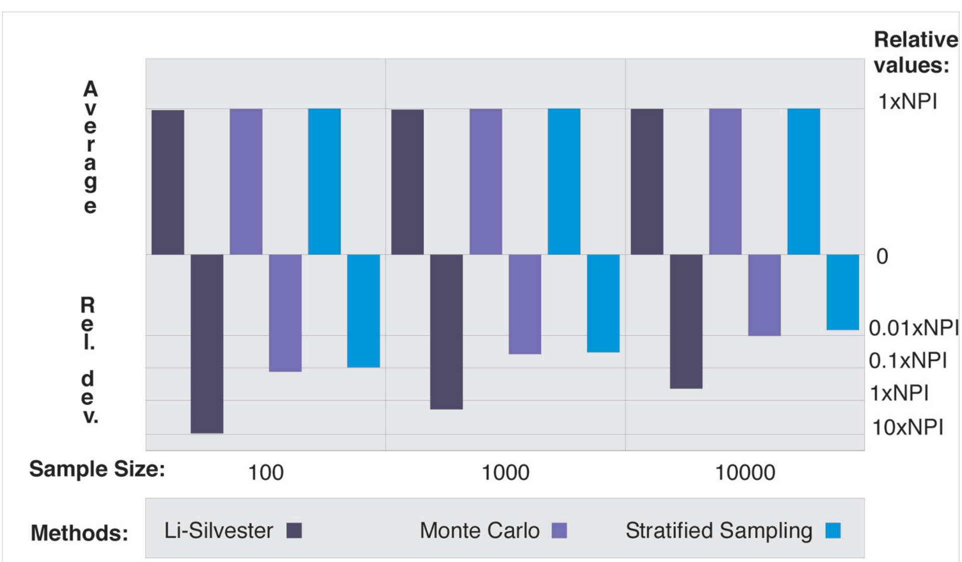

Figure 5: Loss of demand in unprotected case, ($NPI = 2.995 \cdot 10^{-3}$).

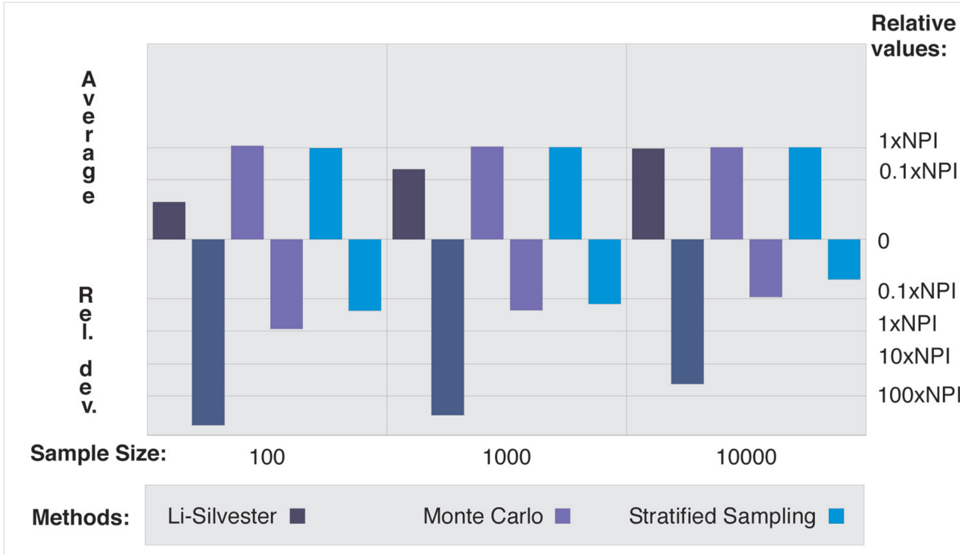

Figure 6: Loss of demand in native layer protection case, ($NPI = 6.6 \cdot 10^{-5}$).

ever, the LS estimation yields a rather poor performance since due to the great number of network elements and therefore, the great number of states, the difference between the upper and lower bounds is rather high even for 10 000 samples. For the other methods the standard deviation is about 10% of the average even for 100 samples and around 5% for 1 000 samples.

In Figure 6 generated for the native layer protection a significant change can be detected where the SONET/SDH layer demands are protected in the SONET/SDH layer and the WDM layer demands are protected in the WDM layer. The average loss decreased almost two orders of magnitude, the PPSS method still produce promising estimations even with only 100 samples, but the standard deviation of the MC method is about 2–3 times higher than the values of the PPSS method. The LS estimation for small sample size has no relevance since the upper bound is more than two orders higher than the lower bound and the lower bound is less than tenth of the real value. Although for large sample size the lower bound is almost accurate for the LS method, the difference between the two bounds is still too large.

Figure 7 shows the results for the multi-layer protection option. The results are very similar to the native layer protection case. In both cases this behavior is due to the

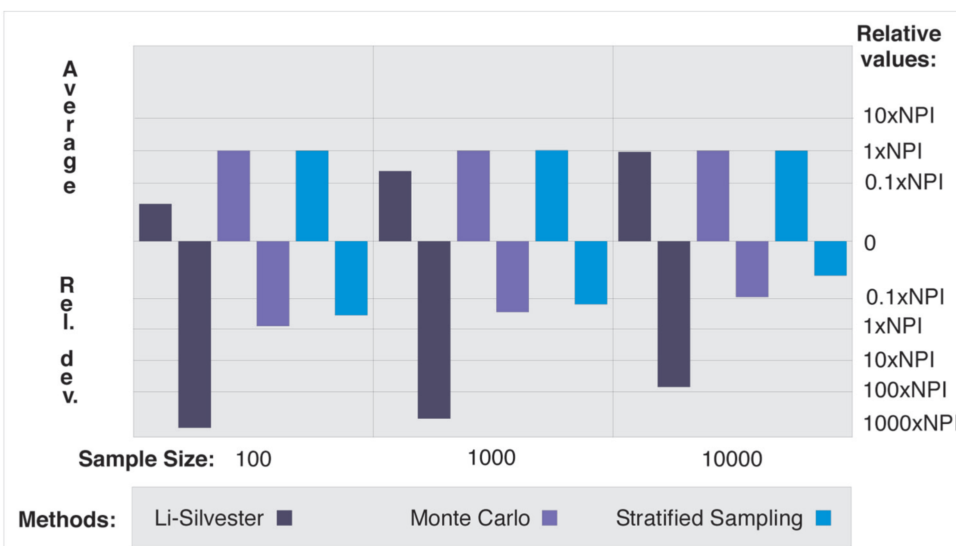

Figure 7: Loss of demand in multi-layer protection case, ($NPI = 5.95 \cdot 10^{-5}$).

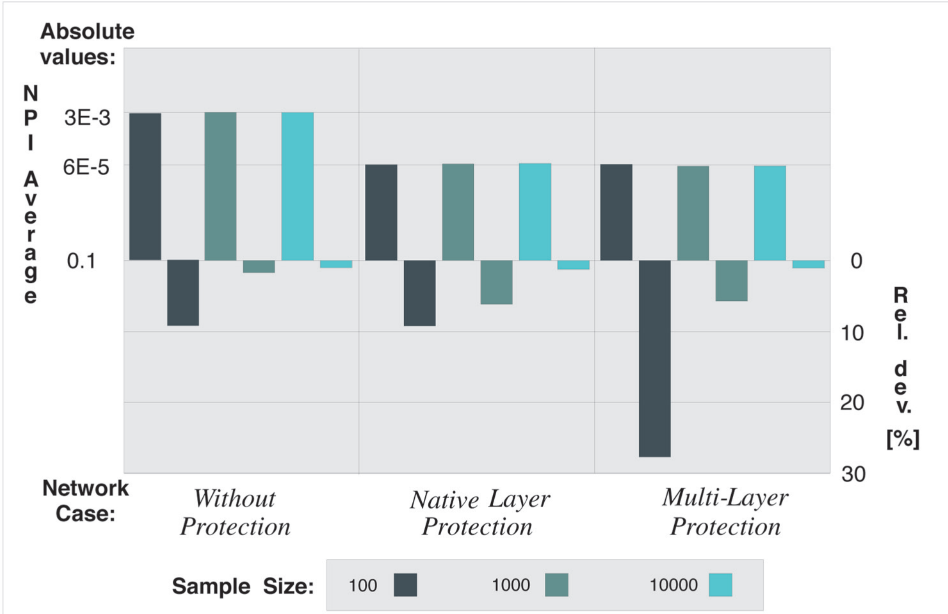

Figure 8: Comparison of estimations in case of different resilience options.

fact that the most probable cable (fiber) single failures are well protected, and therefore most of the states used by the LS method are not relevant, and many of the states chosen by the MC method are also less important in the estimation.

Since the PPSS method seems to be very promising, Figure 8 compares the performance of this method in the case of the different protection options. In this figure the upper part shows the estimated value in logarithmic scale while the lower part depicts the relative standard variation in linear scale. The figure clearly shows what can be expected: the accuracy of the method strongly depends on the order of the estimated value. However, it can be observed, that although the investigated values are about 1/20 of the unprotected value, the relative standard deviation is only about 3 times greater.

5 Conclusions

In the paper the efficiency of the availability analysis methods in case of multi-layer networks is studied. A SONET/SDH over WDM network model is defined with different resilience schemes. Unprotected, native, and multi-layer protection options are evaluated with different analysis methods. The applied analysis techniques are the Li-Silvester deterministic bounds, the Monte Carlo method, and the so-called stratified sampling with a two-phase (pre-screening, post-sampling) solution.

The results clearly show that in case of unprotected networks, when the performance degradation is due to the most probable states with single failures, all methods give acceptable estimates for the availability parameters with few samples, although the upper deterministic bound is far from the real value. On the other hand, in case of well-protected networks the deterministic bounds can provide acceptable estimates only with very high number of samples, while the stratified sampling method produces estimations with relatively small standard deviation (less than 30% of the real value) even in case of only 100 samples.

In the paper the application of stratified sampling is demonstrated only for 1 + 1 protection schemes. Since the reliability model depends only on the failure configuration, the performance index can be determined for restoration schemes as well. However, in case of more complex restoration schemes the calculation of the performance index is much more time-consuming, and therefore, the benefit of the decreased number of necessary samples obtained by the application of stratified sampling becomes extremely important.

On the other hand it can be also observed that the Monte Carlo method resulted in satisfactory good estimation of the real values, but in case of well-protected networks the variance of the experiments is about 2–3 times higher. With other words, in case of well-protected networks the Monte Carlo method requires 5–10 times more samples than the applied stratified sampling method. This property of the stratified sampling can be efficiently utilized in the analysis of other well-protected multi-layer networks. However, some further investigations are required in order to avoid the two-phase sampling process.

6 Acknowledgments

The authors would like to thank János Levendovszky and Attila Kiss for their valuable contribution in developing the application of stratified sampling, and Zsombor Elek and Péter Bajor for the implementation of the analysis method. This work was partially supported by the Hungarian Research Fund OTKA T 030685 project and by the Hungarian Telecommunications Company Ltd.

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