Availability Modeling and Analysis of Optical Transmission Network Architecture - Results from EURESCOM P615 project

Tivadar Jakab¹, Dávid. Arató¹, André Hamel²

1: Hungarian Telecommunications Co. Technical University of Budapest
Department of Telecommunications
H-1111 Budapest, Sztoczek u. 2., Hungary
E-mail: jakab@hit.bme.hu, arato@plan.hit.bme.hu

2: France Telecom CNET DTD/RTO
Technopole Anticipa
22307 Lannion Cedex F
FT-BD/CNET/DTD/RTO
E-mail: andre.hamel@cnet.francetelecom.fr

Abstract

Today’s optical communication systems are only used for point-to-point transmission. Wavelength division multiplexing has been recognized as the key technology to upgrade existing fiber plants to real optical networks. This technological evolution offers additional functionalities due to the applications of optical nodes. Numerous partly or fully optical network architectures based on different optical node configurations can be specified. Extensive study of these optical network architectures is going on to identify the candidate applications on the evolutionary path towards the optical transmission network layer. The improvement of the network availability can be expected due to the applications of highly reliable optical network elements and the additional flexibility and protection can be realized in the optical network domain. This paper presents the modeling and analysis methodology applied in EURESCOM P615 project to study different optical network architectures from availability point of view. An application example with some numerical results is presented, as well.

Keywords: EURESCOM P615 project, optical transmission networks, optical network architectures, Colored Section ring* architecture, reliability/availability modeling, availability analysis.

* Coloured Section Ring technique is covered by a patent owned by France Telecom.
1 Introduction

1.1 Motivations

Today’s optical communication systems are used only for point-to-point transmission. Fundamental network functionalities (routing, protection) are realized in the electrical domain (by SDH or SONET technology). Since there is a huge amount of fibbers in the networks it is obvious that any network operator is highly interested in exploiting this potential. Wavelength division multiplexing has been recognized as the key technology to upgrade existing fibre plants to real optical networks. This technological evolution offers additional functionalities due to the applications of optical nodes. Numerous partly or fully optical network architectures based on different optical node configurations can be specified. EURESCOM P615 project titled Evolution towards an optical network layer is focused to study the evolutionary path in the core and metropolitan area networks towards an optical network layer, describe, model and analyze optical network architectures in details [2, 3]. To identify most promising networking applications and the expected benefits of these optical architectures detailed analysis and comparison of candidate optical and existing SDH architectures (for reference) were elaborated [1].

The improvement of the network availability can be expected due to the applications of highly reliable optical network elements and the additional flexibility and protection can be realized in the optical network domain. Numerous optical architectures with different protection solutions were elaborated and studied in details in national and international projects, e.g. [4,5,6,7]. Reliability and availability are important aspects to evaluate and compare different architectures and to identify relative advantages and drawback of the studied solutions.

Optical transmission networks are under study but still only a few field trials are installed. On the other hand advanced optical transmission equipments like optical add-drop multiplexers and optical cross-connects are not commercialized yet (or the commercialization is in an early stage), the lack of information on equipment implementation and the very limited experiences from operational point of view (e.g. availability characteristics) are the basic problems to be faced studying optical architectures in details. Applied modeling and analysis techniques should take into account these problems.

1.2 Content of the paper

A modeling and analysis methodology applied in EURESCOM P615 to study the availability characteristics of different optical architecture is presented in this paper in general, and with some numerical results in an application example.

First the general approach to availability analysis studies is summarized, and two examples are given how to establish simple equipment and transmission node models taking into account the realizations of fundamental transmission node functionalities.

Then the Colored Section ring architecture is introduced briefly, and the reliability model of the architecture is presented. Finally, the numerical results from the analysis are given and commented and the paper is concluded.
2 General Approach to Availability Modeling

A general availability modeling technique [8] was elaborated to support availability studies of transmission network architectures and this general technique was adopted for optical network studies [1]. Based on this general approach a modeling technique relying on the networking functionalities realized in the nodes of an architecture were developed. The possible implementations of these networking functionalities are derived from available equipment specifications (if available). Based on the detailed reliability information on the equipments reliability data can be derived and assigned to the logical functionalities. With such an approach the relative errors result from the estimations applied to assign reliability parameters to the new functionalities can be minimized and the generality and manufacturer independence of the studies can be kept.

A logical node model can be constructed using the logical functionalities, and the reliability model of the architecture can be established applying the node model. The flowchart is presented on Figure 1.

Having the detailed functional model of the architecture under study the needed node functionalities can be identified (Figure 1 top left). On the other hand based on the information on equipment structure and reliability the logical parts of the equipment implementing different functionalities can be identified and reliability data can be derived and assigned to these functional parts (Figure 1 top right).

Mapping the logical functionalities of the transmission network nodes and the implementation of these functionalities derived from the studies on realistic equipment a node and architecture models can be elaborated for reliability studies (Figure 1 bottom part). Having some simple assumptions for the repair/maintenance policy the model can be extended for availability studies, as well.

![Figure 1. The elaboration process of the reliability model of an architecture](image-url)
2.1 Node functionalities

Routing and protection are the two fundamental complex transmission network functionalities:

- **routing**: cross-connecting transmission systems, or channels realized in these systems to establish transmission routes in the network,
- **protection**: monitoring network elements (or information flows) to identify degradation, alarming, switching and protocol handling (if needed) to reduce or eliminate the impacts and consequences of the network element failures (based on pre-planned spare capacities).

These fundamental functionalities can be realized partly or fully in the optical or electrical network layers. Based on the locations of these realization the network architectures can be classified, and an evolutionary path from today’s networks to optical networks can be envisaged (Figure 2).

![Figure 2 Possible steps for the introduction of optical transmission network functionalities](image)

Going into the details further important functionalities can be identified in transmission networks, like:

- interfacing with clients,
- transmission line termination,
- multiplexing/demultiplexing transmission channels,
- adding/dropping transmission channels,
- regeneration of transmission channels (or entire multiplexed bundles),
- interfacing between electrical and optical network layers.

These functions can be implemented different ways. Different architectures may include different functions (all of them, or just a part), some functions can be realized by different physical implementations.

Both SDH (SONET) and optical transmission network can be described with help of these functionalities.
2.2 Steps to elaborate a reliability model of an equipment

After examining and analyzing the physical structure of an equipment, a general equipment reliability model can be established. This general model consists of different parts. These parts can be used to model the different functionalities in an equipment. These parts can be described with reliability characteristics based on the physical realization of the equipment.

In the modeling an equipment is represented with functional elements (parts) which are physically implemented in the same unit (e.g. card) and/or functionally belong together. These elements are considered two-state ones and a simplified equipment model can be established based on this approach.

The equipment reliability model is derived from the functional and the hardware structure of the equipment, thus this model is unique for each equipment (different implementations or typical solutions can be taken into account). Two examples (one for an electrical and another for an optical equipment) are presented as follows.

The modeled equipments are the ADM and OADM. The models discussed below are applied in the analysis example presented later on.

2.2.1 Model of an ADM

The fundamental parts of the SDH (SONET) ADM equipment can be seen in Figure 3. The ADM has three basic parts: the tributary, the local cross connect, and the aggregate parts. There are some further parts and functionalities (e.g. power supply, clock, control and management units) should be failure free to fulfill the entire equipment functionality. These parts of the equipment are represented by the control element of the model. The local cross connect part has a 1+1 hardware protection (card duplication) because of the importance of the realized functionality.

A general analysis of the equipment structure, based on the specific realizations between different physical and functional parts helps to assign reliability characteristics to these basic parts. (Reliability characteristics are derived from the realistic reliability data of the parts used to realize the equipment.)
After analyzing the equipment in functional and structural points of view the a simplified reliability model of the equipment fitting to the general network model are elaborated. Figure 4 presents the reliability model of the ADM. Each element of the model represent one part of the OADM presented in Figure 3. The tributary part and the aggregate parts are represented by the tributary and aggregate model elements. The local cross connect and the other additional part of the equipment are represented by the LDXC element. This can be done because of the serial impact of these part on the handled demand. (The additional model element on the right side of the Figure 4 is only for general node modeling purposes.)

The model is a bi-directional model because of the transmission demands to be analyzed are bi-directional ones, and both transmission directions should be failure free to realize the studied functionality.

2.2.2 Model of an OADM

The modeled OADM is a grating type one built up of two grating filters. The basic element of an OADM equipment can be seen in Figures 5. This filters realize the add and drop function in the optical domain. If a wavelength is not dropped in the node, it is routed directly between the two filters. A filter is a unidirectional equipment installed on a single optical fibber.

The transmission network architecture realized with the equipment is for bi-directional connections, and all demands to be realized in the architecture are bi-directional ones, as well. In this case two equipments are needed in the two-fibber ring, one for each fibber. (Figure 6/a)
A general analysis, based on the specific realizations can help to describe these basic parts of the equipment with reliability characteristics. (Derives from the data of the used components.) After analyzing the equipment from functional and structural points of view the reliability model can be established (Figure 6).

The two different equipment can be modeled independently in the first step. But because of the bi-directional connections, the applied failure criterion corresponds to the bi-directional service. Thus, the reliability model should be a bi-directional one, and the last step is to develop the bi-directional reliability model of the OADM (See Figure 6/c).

![Figure 6. Reliability model of an OADM](image)

### 3 The Applied Tool

The numerical calculations of the present study were elaborated with help of a computer tool implementing a general transmission network model and analysis method [8]. The basic idea of the model is to apply simplified two-state network elements and a path based description of the given network application. In path based description the detailed routing and capacity informations on demands are given taking into account detailed node models.

Based on this approach different types of performance indexes can be calculated both on demand or overall network levels [8]. Since this study is focused on the general evaluation on availability characteristics of a given architecture, a simplified approach is taken evaluating and comparing the availability of a few typical routes in the architecture. With this simplification the analysis can be focused on the complexity and realization of the architecture excluding the impacts of different demand patterns.

### 4 Colored Section Ring Architecture

As an example for the application of the above summarized modeling technique the availability analysis of Colored Section ring architecture is given.

The basic idea of the Colored Section Ring (CS ring) architecture is to take advantage of the well known linear multiplex section protection (MSP) protocol available in standard SDH ADMs and the wavelength routing in a two-fibber bi-directional optical ring to increase the transmission capacity [9]. Based on several techno-economical analysis and comparison studies [10, 11] it is proved that Colored Section
The advantages of Colored Section ring architecture can be summarized as follows:

- The use of wavelength routing allows an increase in ring capacity, thus full available capacity can be dedicated for working connections (capacities dedicated for protection are separated in wavelength).
- Improved capacity utilizations can be achieved thanks to the extra flexibility provided by the optical layer.
- Reuse of existing SDH equipment, and the compatibility with SDH ring management systems result further economical and operational advantages.

Because of the good compatibility with the standard SDH equipment the colored section ring seems to be a good alternative in the near future to upgrade existing SDH rings or install new ones at a low cost. Colored Section ring can be considered as a promising candidate to introduce optical network layer in the current (metropolitan area) transmission networks.

It is an open problem for the basic Colored Section ring architecture how to provide full protection against node failures. The linear MSP protection included in the architecture does not provide solution for that. There are different options to solve this problem. The application of the presented reliability modeling and availability analysis methods helps to elaborate detailed informations to evaluate and compare different protection solutions applied in the Colored Section ring architecture. After a brief summary of the architecture further extra protection solutions can be applied to protect node failures are analyzed and evaluated from availability point of view.

### 4.1 Node Architecture

In the CS ring the SDH ADMs access the ring via optical add-drop multiplexers (OADM). The purpose of an OADM is to insert a transmit signal from an SDH ADM and extract a received signal to an SDH ADM at a particular wavelength (Figure 7).
The OADM is transparent for other wavelengths not concerning the given node. The transmit and receive signals can be at two different wavelengths, however there are technological limitations towards the total number of wavelengths in a wavelength multiplex.

4.2 Routing

In usual SDH rings the ADMs are connected to their two neighbors using multiplex sections. In Colored Section Rings a particular wavelength is dedicated to each multiplex section (therefore a multiplex section is called a colored section). This solution gives the possibility to connect two ADMs regardless of the physical order of nodes on the ring cabling infrastructure and a logical ring structure can be established (Figure 8).

The CS ring is a multihop optical architecture. But not an all optical one, because the routing functionality is realized in the electrical domain. The route of a transmission demand between two logically non adjacent nodes is set up via the SDH ADMs of the intermediate nodes (Figure 8) through optical/electrical/optical conversions.

4.3 Extra Feature - Logical Ring Layer

Based on to the wavelength routing a logical order of nodes, different from the physical cabling infrastructure can be realized in CS rings. This capability gives the possibility to reduce transit traffic via the intermediate nodes and links and improves the utilization of SDH ADM capacities. Not only the connection order of nodes can be modified in CS rings, but nodes can be multiplied in the same ring, as well. In case of mainly concentrated traffic patterns (e.g. in hubbed network structure) the duplicated insertion of hub nodes can improve the utilization of SDH ADM capacities considerably [11].

In the basic SDH ring dimensioning problem a set of nodes (a network cluster) with fixed connection order and the transmission demands are given, the capacities of the ring links and the ADMs are specified. Generally, the target of the planning process is
to fulfill the demands with minimum network cost (e. g. in a simplified representation with minimum number of ADMs).

As consequences of new capabilities of CS rings new dimensions of the planning problem can be identified. Since in the basic ring dimensioning problem the connection order of nodes is fixed according to the cabling infrastructure, dimensioning CS ring the order of nodes on the logical ring layer is target of optimization.

Taking into account that a node can be duplicated in the same CS ring the number of nodes having a possible access to a given ring system is not fixed either. Generally, the number of nodes to be multiplied strongly depends on the total amount of originated and terminated demands of the nodes and the demand pattern itself.

These features make the CS ring dimensioning problem more complex than the classical SDH ring dimensioning.

4.4 Protection

The “built in” protection against fiber cuts in a Colored Section Ring is provided using the well known standardized MSP protocol. The transmitted signal is splitted and permanently bridged to both the working and protection systems. The decision on which signal to use is made by the receiver end analyzing the signals at the receive terminal. The non-revertive single-ended protection switching is performed in the electrical domain. No transfer of extra information is required simplifying the procedure considerably.

In CS ring architecture the MSP implicates that every optical line interface is duplicated in the SDH ADMs (Figure 7). Working and protection signals are transmitted through the OADM in the opposite directions via the two fibbers. Thus, a connection between two nodes uses two divers routed fiber pairs on the complementary arcs of the ring (Figure 9).
Concerning the node failures the simple category “node failure” is not accurate enough in case of Colored Section ring. Three situations should be distinguished since there are three different functions can be dedicated to a network node from the demand realization (routing) point of view. The three functions are as follows:

1. **Termination**: These are the nodes the demand originates from and terminates. Functionalities realized both in the optical and electrical domains should be failure free to realize this function.

2. **Optical routing (bypass)**: Optical channel bypasses a physically intermediate node. Only the OADM bypass function should be failure free to provide this functionality (it is a realistic assumption that an SDH ADM failure does not affect optical bypass functionality in a node in general.)

3. **Electrical routing (bypass)**: Transmission demands between logically not adjacent nodes should be routed in the logically intermediate nodes in the electrical domain. SDH ADMs are realizing this routing functionality in the nodes (local cross-connect part), thus this equipment (and OADM of course) should be failure free to provide the electrical routing functionality.

Returning back to the protection: endnode failures are not protected in the Colored Section ring. (Note: it is not common in transmission architectures to protect endnode failures. However, there are several hardware protection solutions to protect the failures of the specific functional part of an endnode like tributary. These type of protections are not on the architectural but on the equipment level.)

Concerning the intermediate node failures the two types (from a transmission demand route point of view) of these failures should be distinguished. The failures in the nodes bypassed in the optical domain are protected by the MSP. The failures in the nodes bypassed in the electrical domain (electrical routing nodes) are not protected in the basic Colored Section ring architecture.

### 4.5 Extra protection in Colored Section Ring Against Node Failures

To eliminate the impact of single electrical routing node failures two types of solutions based on two different approaches can be applied.

Extra protection may be introduced to protect electrical routing node failures. Standard SDH MSSP ring over the logical CS ring, or 1+1 path protection are available for this purpose.

Based on a different approach the need of electrical routing functionality can be eliminated with help of the extra flexibility provided by logical node reordering feature.

#### 4.5.1 Multiplex Section Shared Protected Ring over Colored Section Ring

Based on the SDH ADMs in the nodes an SDH MSSP ring can be installed over the Colored Section ring. In this case as it is well known, the available transmission capacities are splitted equally, and half of it dedicated to working connections and the other half is reserved for protection. In case of a single failure (node or link) the nodes adjacent to the failed section switch the failed channels to the reserved protection capacities.
4.5.2 1+1 Path Protection in Colored Section Ring

Application of 1+1 path protection (PP) can also provide the needed extra protection feature in Colored Section ring to protect single electrical routing node failures. In case of 1+1 path protection the information between the source and destination is transmitted via two disjoint routes (complementary arcs of the ring). According to the extra flexibility in Colored Section ring architecture physical and logical ring layers can be distinguished. 1+1 path protection implies disjoint routes on the logical ring layer (Figure 10. Note: this figure is a simplified schematic illustration, more accurate interpretations are given and analyzed in Figures 11., 12. and 13.)

![Logical ring layer](image)

![Physical ring layer](image)

Figure 10   Schematic representation of 1+1 path protection on the logical and physical ring layer with different orders of nodes

Since the physical and logical node orders in the ring can be different in Colored Section ring architecture it can be difficult or even practically impossible to provide two disjoint routes between the source and termination nodes of the transmission demand on the physical ring layer in specific cases. However, with help of the linear MSP available in the Colored Section ring architecture the problem of missing disjoint paths can be solved with the parallel operation of MSP and PP protection mechanisms. Based on some figures a brief analysis of some typical cases or examples of the 1+1 path protection in Colored Section ring architecture (in a small four node ring) are given.
Before starting the analysis some general interpretations are given to the Figures 11., 12. and 13. A small four-node Colored Section ring is represented on the figures. The arrangement of the nodes gives the physical ring configuration (according to the assumed optical cabling infrastructure), the numbering of the nodes gives the logical ring configuration (according to the assumed assignment of the colored section between the node pairs). As it is can be depicted on the figures between the nodes neighboring on the logical layer there are a pair of connections (so called colored sections) represented by the broad lines routed via complementary arcs of the physical ring (because of the linear MSP). The working and protection paths between only one selected pair of nodes are given (on each figure) by solid and dashed lines, respectively. However, the selected node pairs vary (from figure to figure) to present different cases. A working or protection path can pass through a node in the optical domain (in the optical multiplex sections represented by the broad lines) or in the electrical domain (crossing the node box). Note: the parallel sections of the routes due to the 1+1 MSP protected links are not represented on the figures.

In the case analyzed at first (Figure 11) the source (Node 2) and termination (Node 3) nodes are neighboring both on the physical and logical ring layer. In this case it is not a problem to set up disjoint routes, because one route is via the shorter arch (direct link) and the other is via the longer arch of the ring (passing through Nodes 1 and 4 in the electrical domain).

In the second case (Figure 12) the source (Node 1) and destination (Node 3) are neighboring only on the physical layer. In such a case both working and protection routes should be established on the logical layer via intermediate nodes, and depending on the given physical arrangement of nodes there may be no disjoint routes. It is the case when the destination (Node 3) is closer to the source (Node 1) then one of the logical neighbors of the source (Node 4).

In the third case (Figure 13) the source and destination is neighboring only on the logical layer. In such a case a direct (working) route can be established only via physical neighbors. The protection route is via the other logical neighbors of the source and destination. In such a case depending on the given arrangement of nodes problems with disjoint routes also may occur.

In cases when disjoint pair of routes is missing the combined application of 1+1 path protection and linear MSSP solves the problem of link failures with overlapped working and protection routes, and the problem of common node failures, as well. The protection of link failures by linear MSP is obvious, the protection of failures in nodes passed both by working and protection routes may need some clarification. If the same node is passed both by the working and protection routes of a transmission demand there are two cases:

1. Both bypasses in the optical domain.
2. One bypass in the optical and the other in the electrical domain.

The case of both bypasses in the electrical domain is excluded obviously, because the working and protection route is definitely disjoint on the logical ring layer (based on the basic idea of 1+1 path protection).

Since the failure in a node bypassed in the optical domain is protected by the linear MSP, no catastrophic single node failure exists in the Colored Section ring with extra 1+1 protection. (In above Case 1 both failures, in above Case 2 one failure is
protected, thus after the single ended protection switching action at least one failure free route is available.)

![Diagram](image)

**Figure 11** 1+1 path protection for demand between both logically and physically neighboring nodes (Nodes 2 and 3)

As a logical continuation of the previous analysis a fourth case 1+1 path protection between neither logically nor physically neighboring nodes should have come here, however this case is not analyzed, because it is not present in this small four node example. (In a larger example it would have been too complex to follow the optical channels and the routing over them.) In general the problems with disjoint routes may exist depending on the arrangement of nodes in this case, as well.

The combined application of linear MSSP and 1+1 PP needs further study from an operational point of view. However, since there are no disjoint paths in some particular cases and the failure of a common link or node is protected by linear MSP it seems to be reasonable to have such a timing in protection switching when linear MSP reacts first in case of failures.
Figure 12  1+1 path protection for demand between only physically neighboring nodes (Nodes 1 and 3)

Figure 13  1+1 path protection between only logically neighboring nodes (Nodes 3 and 4)
4.5.3 Node Reordering on the Logical Ring Layer

A fundamentally different solution can be developed to protect intermediate electrical routing node failures based on the extra architectural feature of Colored Section Ring. Finding appropriate logical node order the need of the intermediate electrical routing node functionality can be eliminated. To achieve such a solutions different logical ring may be needed to realize a given demand pattern. The logical rings should be set up with such node orders that demands only between logically neighboring nodes are realized in each ring. In this case no need of electrical routing functionality in intermediate nodes, because each source-destination pairs are neighboring on the logical layers of different rings, Figure 14 and 15 give an example of that. (The numbering of the nodes on the figures represent the physical node order, the arrangement is the logical one.)

A five node full mesh demand pattern is taken to illustrate the solution (Figure 14, left side). If the demands realized without node reordering (Figure 14, right side) half of the demands are between nodes not neighboring on the physical layer, thus routed in the electrical domain in intermediate nodes on the logical layer. The demands can be separated and two Colored Section ring architectures with different orders of nodes on the logical ring layer can be applied to realize them (Figure 15, separated demands on the left, realization with different logical node orders on the right).

The first ring is with same physical and logical node orders realizing five demands, the logical node order is properly modified in the second ring to realize the rest of the demands. As it can be depicted on Figure 15 (right side figures) each demand is between nodes neighboring on the logical ring layer. There is no need of intermediate electrical routing node functionalities in the solution presented by Figure 15. Thus no impact intermediate electrical routing node failures exists. In such a solutions linear MSP provides satisfying protection in the architecture. (In this analysis it is not taken into account that PP and liner MSP depending on the given realizations may protected different functional parts of the termination nodes.)
4.5.4 General Evaluation and Comparison of Different Protection Solutions

Linear MSP is included in Colored Section ring architecture as fundamental protection. Since the dominating failure is the fiber cut in optical transmission networks and linear MSP protects single link failures this solution may be enough in numerous applications. This basic implementation has been extensively studied [10, 11], and based on the results of this studies the main conclusion are as follows:

The cost of CSR is very sensitive for the cost of optical tributaries because of the applied protection technique. However, in a wide cost range the CS ring is less expensive in many network applications than the classical PP or MSSP SDH rings. The cost comparisons presented in [10, 11] show that CS rings can be realized with a lower cost in a metropolitan network area in most cases. In case of large total originating and terminating demands of nodes the application of SDH ADMs with 24 STM-1s tributary capacity in CS rings is cost effective.

Figure 15: An example how to apply proper logical rings to protect demands in Colored Section ring

Evaluating the extra protection realized by the application of SDH MSSP ring technique it is an open question how to operate linear MSP and MSSP ring in parallel (timing of the different management actions). On the other hand it is obvious, that the advantages from the utilization of the total available transmission capacities in Colored Section ring are lost, only the extra feature of node reordering is kept. The
problems and solutions of this harmonized operation needs further studies from OAM points of view. Since (besides the open operational problems) applying MSSP ring over CS ring to protect intermediate node failures leads to the loss of some fundamental economical advantages of the CS ring architecture this option is not studied in details.

Concerning the application of 1+1 path protection in Colored Section ring the capacity consumption is increased, and the flexibility of capacity (bandwidth) reuse is lost, because the total realized 1+1 protected demand capacity loads each link on the logical ring layer. To realize and operate such an architecture a proper solution in the management processes for harmonized timing of protection switching for linear MSP and 1+1 PP is needed.

Logical rings with different node orders seem to be the most promising solution to improve the protection of the basic architecture. In this case the logical node orders are optimized to have demands only between logically adjacent nodes. Thus, no electrical routing function is needed in intermediate nodes, and the impact of intermediate electrical node failures is eliminated. (Optical bypass is protected by the linear MSP). The price of that should be paid in the less attractive filling rates of transmission systems which may increase the installation costs. (Of course this kind of disadvantage strongly depends on the demand pattern to be realized.) Dimensioning the basic architecture without any extra protection the node reordering is target of optimization to minimize capacity utilization. If the node reordering is defined to improve protection this flexibility is lost from a dimensioning point of view. (Further studies are needed to analyze the consequences of this change.)

A mixed solution: node reordering to minimize needed transmission capacity, and 1+1 path protection only for demands between not logically neighboring nodes may also be a promising solution. (Also further studies are needed to analyze this combination and compare with the previous one with dimensioning and installation cost points of view.)

After a general analysis and evaluation a detailed availability study is presented to compare the availability performance of the different solutions.

5 Availability Analysis of Colored Section Ring Architecture with Different Protection Solutions

5.1 The Problem To Be Studied

Three different basic solutions are available to realize protection in Colored Section ring architecture. (MSSP over Colored Section ring was excluded based on a general analysis in Chapter 4.5.4.). The main goal of the analysis to evaluate and compare the different variations of the Colored Section ring architecture from availability point of view.

5.2 Analysis Approach

There are several availability characteristics and methods to the describe and analyze an architecture. The definition of some of them (applied in the presented study) are as follows:

- Fit: a measurement unit, 1 Fit equals $10^{-9}$ 1/hour.
- **MFR**: mean failure rate, gives the mean value of the number of failures which is occurred in one hour.
- **MTTR**: mean time to repair, gives the time between the failure and the end of the repair process.
- **MDT**: mean down time, mean value of the time in out of order state(s).
- **MUT**: mean up time, mean value of the time in working state(s).
- **DTR**: down time ratio, \( DTR = \frac{MDT}{MDT + MUT} \), gives the rate of the out of order time and the total system time of the different demands.

A general network level analysis evaluates the realization of the entire demand pattern based on Network Performance Index calculations [8]. Since the presented study is focused on the general evaluation of an architecture (and not on evaluation and comparison of given networking applications) a simplified approach can be applied.

Characteristic routes can be identified in the architecture. These characteristic routes can be applied for working and protection routing of the transmission demands. Having the set of these characteristic routes some typical demands can be specified. These demands are considered typical, because they are realized by characteristic (feasible) combinations of characteristic working and protection routes.

If the analysis is focused only on a few typical demands and not on a (or some) demand patterns, the impact of the different demand patterns can be eliminated, and the architecture can be studied on a simplified basis.

(Note: in case of large mesh architectures the number of typical routes can be high, thus no practical gains from typical demand approach.)

The main steps of the typical demand analysis are as follows:

1. **General structure of the architecture** ⇒ **Typical routes** ⇒ **Typical demands**
   - Based on the analysis of the general structure and topology of the architecture typical routes (e.g. taking into account the different number of crossed functional components) can be identified.
   - Typical demands can be specified to study the characteristic (feasible) combinations of typical working and protection routes.

2. **For the architecture**
   - **Development of the simple schematic model of the architecture.**
     - In this step the architecture is analyzed. The types of needed functionalities and equipment are identified, the realization of working and protection routes are described.
   - **Development of the functional model of the architecture.**
     - In this step the different functions of network elements and the implementations of the working and protection routes are analyzed to identify defining functionalities (e.g. add, drop, bypass, cross connect functions in electrical and/or optical domain).
   - **Specifications of reliability model of the nodes and the architecture.**
     - In this step the reliability model of the architecture is described with the help of the information on the node implementations, the reliability model of several
equipment, the reliability model of nodes. The model can handle the different paths of working and protection routing of demands.

3. Calculation of the Down Time Ratio (DTR) for the different routes.
   During this step the availability characteristic of each route can be calculated based on the established reliability model, and the availability data of the network elements.

4. Availability of typical routes ⇒ Calculate or estimate, and evaluate availability of typical demands
   In this step the availability characteristic of typical demands can be calculated or estimated with the help of the availability information of their routes. Because of the path level representation of the demands exact calculation can be done in case of 1+1 path protection. If the protection routes depend on the failure states (MS level protection, restoration), an estimation (worst case and/or best case evaluation) is given to describe the typical demands.

In the presented study the analysis evaluates only single STM1 capacity demands. The method analyses the possible typical paths of the architecture. The elements of the models are described with MFR and MTTR values, the result of the analysis is the DTR of each demand.

5.3 Reliability Model of the Colored Section Ring Architecture

In case of Colored Section ring, a physical and a logical ring can be separated. The number and the order of the nodes can be different in the two rings taking into account some basic constraints. The only exception is when the node logical reordering feature is used to improve the protection performance.

The architecture contains ADMs, OADMs, and optical fibers. One ring is realized with two fibers. The five node architecture has two different typical demands, containing a single or a double span. The simple architectural model of the architecture and two typical demands can be seen in Figure 16., and Figure 17.

The functional model of a logically single span demand can be seen in Figure 18. The functional model of the logically double span demands can be seen in Figure 19. Because of the complicated routing of the double span demand, the functional model shows routings of the different spans beside each other. Thus two rings can be found in the picture, but in the reality these rings are physically the same. Some nodes are presented several times in case of multiplied usage.
Figure 16. Simple architectural model of CSR with no extra protection in case of 5 nodes for a single span demand

Figure 17. Simple architectural model of CSR with no extra protection in case of 5 nodes for a double span demand

Figure 18. Functional model of CSR with no extra protection in case of 5 nodes for a single span demand
5.3.1 The node model

The structure of the node model is based on the equipment installed in it. A node model is built up from the elements of the model of used equipment. (e.g. see one node in Figure 20, see list of acronyms at the end of the document). If the number of a given equipment in the node is more then one e.g. for capacity reasons the model can be extended.

5.3.2 The architecture model

The reliability models of an architecture is built up from the reliability models of the nodes, which are based on the equipment models. An architecture model contains the node models, and the connections between the node pairs (fiber spans). Additional information as the applied routing and protection can be taken into account in this step of modeling. An example of the reliability model for the studied architecture can be seen in Figure 20.

The reliability model of the five node architecture and the reliability model of the two different typical demands can be seen in Figure 20, and Figure 21. The model elements (represented by vertexes) passed more then once by the studied routes are distinguished in Figure 21. (painted darker). According to the modeling process presented on Figure 1. the equipment models can be seen in section 2.2. These models of ADM and OADM are used in modeling the CSR ring.

Note:

*Without node reordering the logical and physical rings are the same, one logical hop is one physical span. Defining an appropriate logical node reordering each transmission demand can be realized via one logical hop, however the number of physical hops realizing a logical hop depends on the given physical and logical node locations.*
Figure 20. Reliability model of CSR with no extra protection in case of 5 nodes for a single span typical demand

Figure 21. Reliability model of CSR with no extra protection in case of 5 nodes for a double span typical demand
Colored Section Ring with extra protection

The basic reliability model of the Colored Section ring architecture with extra 1+1 protection is the same as the one with no extra protection. The only difference is because of the demands are duplicated and routed in parallel by the two complementary arcs of the logical ring.

Supposing no difference between the logical and physical ring layer the typical demands are distinguished by the number of hops in their routes. (The number of physical and logical hops are the same in this case).

In case of extra protection realized by node reordering the architectural model is the same, but all the typical demands are with single logical hop. In this case the typical demands are distinguished only by the number of physical hops in their routes.

5.4 Numerical Results and Analysis

The flexibility to create a logical ring (with order of nodes different from the physical one) is an extra feature in Colored Section Ring architecture. This additional flexibility can be used not only to optimize the capacity load on the ring, but for achieving better availability results without any extra protection. (Note that the protection in Colored Section ring is originally based on linear multiplex section protection, not protecting intermediate node failures in case of bypassing a node in the electrical domain.) Reordering a CSR ring is to create a new ring order, where physically non adjacent nodes can be logically adjacent. In this case a logical architecture can be achieved where all the demands are single span routed logically. These logically single span demands can be realized by one, two or more physical spans, depending on the original physical locations on the nodes. Colored Section Rings with different solution for protection is analyzed to compare the efficiency of the different protection techniques.

There are three solution are under study:
1. basic Colored Section ring - no extra protection (referred as CSR)
2. Colored Section ring with extra 1+1 path protection (referred as CSRPR)
3. Colored Section ring with reordered nodes on the logical layer to have only logically single span demands (referred as CSRREO).

The resultet DTRs of this analyzes for the single STM1 (155 Mbps) capacity typical demands in architectures with 5, 6, 7, and 8 nodes are as follows. (Analyzed typical demands are between nodes from 2 up to 4 physical spans away from each other.)

<table>
<thead>
<tr>
<th>5 nodes</th>
<th>2 phys.spans</th>
<th>1 phys.span</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSRPR</td>
<td>2.5306E-05</td>
<td>2.5271E-05</td>
</tr>
<tr>
<td>CSRREO</td>
<td>2.5333E-05</td>
<td>2.5298E-05</td>
</tr>
<tr>
<td>CSR</td>
<td>3.4675E-05</td>
<td>2.5298E-05</td>
</tr>
</tbody>
</table>

Table 1 Results from a 5 node architecture
Based on the results in Table 1 the CSR without extra protection differs from the two others only in case of two physical span routes, because of the not protected intermediate node failure. CSR with 1+1 PP is slightly better then the reordered one, because 1+1 PP (together with the built in MSP) provides multiplied protection.

<table>
<thead>
<tr>
<th>6 nodes</th>
<th>3 phys.spans</th>
<th>2 phys.spans</th>
<th>1 phys.span</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSRPR</td>
<td>2.5360E-05</td>
<td>2.5342E-05</td>
<td>2.5288E-05</td>
</tr>
<tr>
<td>CSRreo</td>
<td>2.5391E-05</td>
<td>2.5374E-05</td>
<td>2.5320E-05</td>
</tr>
<tr>
<td>CSR</td>
<td>4.4108E-05</td>
<td>3.4723E-05</td>
<td>2.5320E-05</td>
</tr>
</tbody>
</table>

Table 2 Results from a 6 node architecture
There are three physical span routes in a 6 node ring, thus the impact of the not protected intermediate node failures are more significant in the pure CS case (see Table 2 and Chart 2). The two other cases are very close to each other. (The difference between them in of order $10^8$.)

<table>
<thead>
<tr>
<th>7 nodes</th>
<th>3 phys.spans</th>
<th>2 phys.spans</th>
<th>1 phys.span</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSRPR</td>
<td>2.5413E-05</td>
<td>2.5377E-05</td>
<td>2.5306E-05</td>
</tr>
<tr>
<td>CSRREO</td>
<td>2.5450E-05</td>
<td>2.5414E-05</td>
<td>2.5343E-05</td>
</tr>
<tr>
<td>CSR</td>
<td>4.4177E-05</td>
<td>3.4769E-05</td>
<td>2.5343E-05</td>
</tr>
</tbody>
</table>

Table 3 Results from a 7 node architecture

In 7 node example only the protection paths are increased, thus the general picture is very close to the 6 node case (Tabel 3 and Chart 3).

<table>
<thead>
<tr>
<th>8 nodes</th>
<th>4 phys.spans</th>
<th>3 phys.spans</th>
<th>2 phys.spans</th>
<th>1 phys.span</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSRPR</td>
<td>2.5484E-05</td>
<td>2.5466E-05</td>
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<td>2.5324E-05</td>
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<td>CSRREO</td>
<td>2.5526E-05</td>
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</tr>
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<td>CSR</td>
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<td>4.4245E-05</td>
<td>3.4814E-05</td>
<td>2.5366E-05</td>
</tr>
</tbody>
</table>

Table 4 Results from a 8 node architecture

There are some 4 span routes in an 8 node ring network besides the shorter ones. This example shows the strong impact of the intermediate node failures on the pure Colored Section ring, and the practically no impact of the increased route length on the two other solutions.
Based on the above results it can be seen that the Colored Section ring without any extra protection is affected by the intermediate node failures in multiplied physical span cases.

The results of the reordered and path protected CSR are practically independent of the number of spans in all cases. The multiplied protection in CSR with 1+1 PP and built in 1+1 MSP results the best availability performance. However, the performance of the node reordering version is very close to the path protected one. Based on this results there is no significant gain from the multiplied protection in 1+1 path protected solutions, however, the extra path protection needs additional transmission capacity. The CSR with node reordering is comparable with the 1+1 path protected solution from availability point of view, has no extra OAM aspects (no parallel operation of two protection schemes like MSP and PP in the other case).

6 Summary and conclusion

Based on the above presented results two sets of main conclusions can be drawn. The first set of conclusions refers to the applied modeling and analysis technique:

- The presented modeling technique and methods can be applied successfully to analyze the availability of optical transmission network architectures.
- The modeling technique supports the modeling of new not commercialized equipment (because the modeling is performed on the functional basis) and the reliability calculations if there is lack of information (relative or estimated reliability values can be assigned directly to the functions or to the components releasing a function).
- Electrical, optical (all optical as well) architectures can be modeled and the reliability calculations and analysis can be performed with the presented technique.
- Based on the presented modeling technique networking applications of different SDH (SONET) and optical architectures can be evaluated calculating the expected
relative network performance index, as well. Based on such type of characteristic the availability performance of the networks can be evaluated taking into account the impacts of different demand patterns.

Protection solutions in Colored Section ring are summarized and briefly analyzed in this document. It is identified that in networking applications the linear MSP built in the basic Colored Section ring architecture may not enough to meet the QoS specifications of the demands to be realized because of the not protected intermediate node failures.

Based on the analysis of the available extra protection solution, the conclusions can be summarized as follows:

- With proper node reordering the protection ability of Colored section ring can be improved, the availability performance for this solution is practically the same as for extra 1+1 path protection, however, the node reordering seems to be better from capacity utilization point of view.

- Application of 1+1 path protection has significant advantages from operational point of view comparing with MSSP over Colored Section ring solution.

- A mixed solution of node reordering and 1+1 path protection can be even more promising depending on the given transmission demand pattern to be realized by the network.

- Further dimensioning studies and comparison are needed to provide detailed analysis and comparisons on the capacity utilization of different solutions.

7. Acknowledgments

The authors wish to thank the valuable comments of the contributors of EURESCOM P615 project from the participating companies:


The discussions in the project helped to improve the results presented in this paper.

The publication of this paper was supported partly by the Hungarian Ministry of Culture and Education (FKFP 0420/1997 and MKM-PFP 4349 projects).

8. Note

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9 References

[1] EURESCOM Project P615 Evolution towards an optical network layer (see EURESCOM Web Site: www.eurescom.de)
[4] EURESCOM Project P413 Optical Networking (see EURESCOM Web Site: www.eurescom.de)
# 10 Glossary of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADM</td>
<td>SDH (SONET) Add Drop Multiplexer</td>
<td>MSP</td>
<td>Multiplex Section Protection</td>
</tr>
<tr>
<td>AGGR</td>
<td>Aggregate</td>
<td>MSSP</td>
<td>Multiplex Section Shared Protection</td>
</tr>
<tr>
<td>AGGRE</td>
<td>East Aggregate (in ADM)</td>
<td>MTTR</td>
<td>Mean Time to Repair</td>
</tr>
<tr>
<td>AGGRW</td>
<td>West Aggregate (in ADM)</td>
<td>MUT</td>
<td>Mean Up Time</td>
</tr>
<tr>
<td>CS</td>
<td>Colored Section</td>
<td>MUX</td>
<td>Multiplexer</td>
</tr>
<tr>
<td>CSR</td>
<td>Colored Section Ring</td>
<td>OADM</td>
<td>Optical Add Drop Multiplexer</td>
</tr>
<tr>
<td>CSRPR</td>
<td>Colored Section ring with extra protection</td>
<td>OXC</td>
<td>Optical Cross Connect</td>
</tr>
<tr>
<td>CSRREEO</td>
<td>Colored Section ring with node reordering</td>
<td>PI</td>
<td>Performance Index</td>
</tr>
<tr>
<td>DMUX</td>
<td>Demultiplexer</td>
<td>PP</td>
<td>Path Protection</td>
</tr>
<tr>
<td>DTR</td>
<td>Down Time Ratio</td>
<td>PS</td>
<td>Protection Switching</td>
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<tr>
<td>DXC</td>
<td>Digital Cross Connect</td>
<td>SDH</td>
<td>Synchronous Digital Hierarchy</td>
</tr>
<tr>
<td>EAST</td>
<td>East aggregate part of an ADM</td>
<td>SONET</td>
<td>Synchronous Optical Network</td>
</tr>
<tr>
<td>EPS</td>
<td>Electronical Protection Switch</td>
<td>STM</td>
<td>Synchronous Transport Module</td>
</tr>
<tr>
<td>N, n</td>
<td>Node (on figures)</td>
<td>SW</td>
<td>Software</td>
</tr>
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<td>LDXC</td>
<td>Local Cross Connect Part of an ADM</td>
<td>TM</td>
<td>Terminal Multiplexer</td>
</tr>
<tr>
<td>LT</td>
<td>Line Termination</td>
<td>TRIB</td>
<td>Tributary part of an ADM</td>
</tr>
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<td>MDT</td>
<td>Mean Down Time</td>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
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