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AVAILABILITY MODELING OF MULTI-SERVICE ALL-OPTICAL TRANSMISSION NETWORK

MODELIRANJE RASPOLOŽIVOSTI VIŠEUSLUŽNE SVEOPTIČKE PRIJENOSNE MREŽE

DOCTORAL THESIS
DOKTORSKA DISERTACIJA

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1.

Introduction

The functionality of existing optical transport networks is in most cases limited to pure capacity increase by the application of wavelength division multiplexing (WDM).

Optical networks carry high volumes of telecommunication traffic, and their ability to provide service to clients (or client layers) is of high importance to a telecommunication operator and its clients. As an example, consider an optical fiber using WDM with 100 wavelength channels and bit-rate of 10 *Gbit/s* per wavelength channel. Furthermore, assume that the fiber carries voice channels only (64 *kbit/s*), and that the average load per voice channel is 0.5 *erl*. Assuming that the price per minute of voice call is 2 US cents, the optical fiber provides income to the telecommunication operator of more than 200 million US$ per day. One should keep in mind that in optical cables a number of optical fibers reside. Therefore, even such simple model, limited to a single fiber, emphasizes the importance of optical network resilience to failures.

Loss of service means loss of income to the network operator, but to its clients as well, as they might have their own clients, and businesses relying on the availability of the service. The income loss can be ascribed to following causes;

- Direct, because service was not provided and service provisioning cannot be charged,
- Indirect, in penalties, due to the possibility that service level agreement was not fulfilled, and
- Indirect, due to the bad effect the loss of service will have on users, which may, as a consequence to the service loss, turn to other operators.

Resilience to failures of an optical network, in literature usually termed *survivability*, is a critical issue. Nowadays, main clients of optical networks, in terms of technology, are SDH and IP. In most cases survivability schemes are implemented in higher/client layers, either through dynamic routing schemes, as in IP, or well understood and mature protection and restoration schemes defined by SDH/SONET standards.

The availability, defined as the probability that considered entity will be in non-faulty state at given instance of time, as a generic probabilistic survivability measure, can be used to asses (or estimate) other survivability performances as well. For example, availability can be used to estimate expected number of minutes per year in which given entity will be in faulty state. In the next step, the number of faulty minutes can be used to assess/express the loss of income in a way similar to the presented example.

In the thesis, the objective is to compare and analyze different network architectures in terms of survivability, or ability to provide service even in case of failures. The architectures are defined by their switching, topological and protection and restoration paradigms. Transport entities, definition of which depends on the optical network architecture, can be viewed as an instrument through which all-optical transport network is providing service to its clients. Therefore, the availability of transport entity indirectly estimates loss of income.

Availability analysis requires the calculation of transport entities availability. Owing to the fact that transport entities rely on the underlying optical components being in non-faulty state, availability of a transport entity is calculated as a function of optical component availabilities. The complexity of a function defining the relationship between availability of a transport entity and availability of corresponding optical components depend on the level of detail used for description of optical transport network. In the thesis, the level of detail reaches optical components such as optical fibers, and amplifiers. Depending on the size of the network, defined in terms of nodes and links, this can lead to tens of thousands of optical components, and therefore the corresponding number of variables in the transport entity availability function. In certain cases, transport entity availability functions can be estimated analytically, but in many cases, due to the high level of detail, only simulation methods can be applied to the estimation.

Availability of the optical transport network is one, but by no means the only critical issue in optical networks. Intelligent and efficient protection and restoration schemes aim at increasing the network's resilience to failures, both in terms of service availability and restoration in the case service disruption occurs. Intelligent protection and restoration schemes require implementation of intelligence in the optical network. The intelligence is used primarily in dynamic and automatic service provisioning, but also for implementing different protection & restoration and topological paradigms.

Fiber-optics, through the application of WDM, is the only imaginable answer to the ever increasing telecommunication traffic demands. In the high level view, today's network architectures can be viewed as ones providing different services through different switching paradigms. For example, main services today are circuit switched, used to carry voice traffic and provided through the SDH/SONET, and datagram/packet transfer, provided through the IP. Aforementioned traffic growth will, sooner or later, in the view of the thesis author, require descend of intelligence, or part of it, from higher layers, e.g. IP or SDH/SONET, to the optical layers. The concept of Automatically Switched Optical Network (ASON) is the first step in the direction that is already taking place. Circuit switching service provided by the optical network is a matter of reality. The next possible step towards multi-service optical network will be the implementation of optical packet switching, or optical burst switching as an intermediate step towards optical packet switching.

Previous lines explained the motives behind the title of the thesis; Availability Modeling of a Multi-Service All-Optical Network. Organization of the thesis is as follows: The second chapter presents an overview of the existing optical transport network architectures. In the chapter mathematical description of the optical network referenced throughout the thesis is given. The thesis defines three paradigms used for defining the functioning and behavior of the optical transport network. Namely, they are switching, topological and protection and restoration paradigms.

Description of the proposed all-optical network architecture is presented in the third chapter. In a way similar to the existing network architectures, the proposed architecture defines three fundamental service classes provided through different switching paradigms; circuit, switching and burst. Ascribable to the fact that different service classes are provided by the network, in the thesis term Multi-Service Photonic Network is used to denote a network providing such services.

In the fourth chapter, availability modeling issues are discussed. The chapter presents availability calculation procedures, both analytical and simulation. Transport entity availability models for switching paradigms are also presented.

In order to be able to make availability analysis, a software model of an analyzed optical transport network should be created. The fifth chapter presents design procedures used for creation of optical transport network software model. In design procedures, a use of general heuristic search techniques has been emphasized. Due to that fact, the chapter also presents object oriented framework for optimization and design termed Nyx. The Nyx is based on general heuristic search techniques, such as Genetic Algorithms, and can be easily applied to a number of optimization problems.

The sixth chapter presents the availability analysis. In the first part of the chapter, availability analysis of the considered topologies is presented. Two switching paradigms, circuit and packet, together with the topological paradigm of p-cycles, have been analyzed. In the second part of the chapter, results of the sensitivity analysis have been presented. The aim of the analysis is to identify critical optical components in terms of availability. In addition, viewed from a different perspective, the analysis also identifies components for which availability data are most influential to the availability of transport entities.

2.

Architectures of Optical Transport Networks

The chapter discusses some issues regarding the architecture of optical transport networks. First, an overview of types and services in communication networks is given. The current and future telecommunication network architectures are discussed in short. Highly abstract view of the optical transport network is given, followed by mathematical description. Definitions and terms presented in the chapter are used throughout the thesis. The chapter also gives an overview of switching paradigms in the context of optical transport network. This is followed by the description of protection and restoration paradigms, used to increase network's ability to survive failures. Next we give an overview of what we call in the thesis topological paradigms, such as ring, mesh and p-cycle based networks. Finally, chapter gives a brief overview of the control and management functions within the optical transport network.

2.1. Types and Services of Communication Networks

Generally speaking, there are two types of communication networks. In the first type channel or circuit switching is predominantly used. In such switching scheme, users have guarantees on limits for an end-to-end delay variation, so one may conclude that this kind of switching is useful for services with stringent requirement on time relationships in order to have successful communication. Examples of such network technologies are PDH (Plesiochronous Digital Hierarchy) and its successors SDH (Synchronous Digital Hierarchy) and SONET (Synchronous Optical Network).

On the other hand, computer networks historically use packet switching. In such networks statistical multiplexing is inherently used in order to use transmission capacity more efficiently. Trouble is, quite complex techniques have to be used in order to be able to provide certain degree of quality of service (QoS) guarantees, such as end-to-end delay variation under required limits. Although some of these techniques are quite successfully implemented and used in commercial networks, there are lots of unresolved standardization issues. Hence, such solutions usually work only among products of the same manufacturers. Sometimes even this is not the case. In addition, QoS mechanisms are usually not consistent among networks of different operators. Examples of technologies that rely on packet switching are X.25, Frame Relay, and omnipresent TCP/IP architecture.

A few words on ATM technology should be mentioned at this point. ATM is based on specific switching scheme that tries to take best from both packet and circuit switching worlds. The mechanism is called cell switching, in that cells are special types of packets, small and of fixed size. By keeping cells relatively small and of fixed size, one can provide QoS guarantees. For example, one can reserve every third cell for certain service, and thus effectively provide circuit emulation. On the other hand, we can make no reservation of cells whatsoever, and say to some services “make use of available, free cells”, and thus effectively provide pure statistical multiplexing.

2.2. Telecommunication Network Architectures

In a one view of evolution of communication networks, telecommunication networks are much older than computer ones. Without making significant mistakes, one can instead of telecommunication network say PSTN, or Public Switched Telephone Network, since these networks are built around voice transfer service. On the other side, growth of computer network is directly related to increase in computing power. Naturally, since telecommunication network was already in place, it was usually used as a carrier for computer (data) communications.

This is the reason why modern network architectures use circuit switching at lower layers. For example, SDH/SONET networks, in addition to voice traffic, are nowadays used for transfer of ATM cells, X.25 packets, and Frame Relay. This architecture is depicted in Figure 2.1.

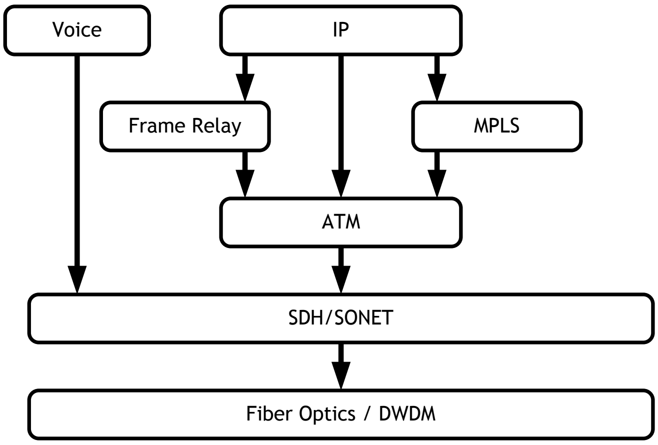


Figure 2.1. – Protocol stack of a telecommunication network

Such architectures are both expensive to install and to manage, and complex in terms of maintenance and configuration. For example, each layer is realized by functionally different physical components. Frame Relay access devices and switches usually do not have much in common with ATM switches. The same holds for IP routers. The final result is network with large amount of inhomogeneous equipment, and large amount of knowledge and work force needed to operate such network.

The main goal to every telecommunication operator is to make money, and one way of making more money is to reduce both investment and operating costs. This is the reason why telecommunication operators have ever present desire to make network architecture as simple as possible, that is, to reduce number of layers.

This reduction can be viewed through the prism of service integration. Not so long ago, an initiative called Broadband Integrated Services Digital Network (BISDN) was based on ATM and SDH/SONET beneath. In such architecture, a transfer of IP data traffic should take place through ATM switches. Furthermore, ATM, at least nowadays (and most probably this will be the case in the future) is almost never used to connect relatively large distances (100 km and more). Instead, beneath ATM, SDH/SONET networks are used to carry ATM cells. Finally, on the physical layer, the optical frequency division multiplexing (OFDM) can be used to extend the capacity of optical fiber. In order to stress its optical nature, OFDM is almost always in literature referenced as wavelength division multiplexing (WDM). In short, such an approach is called as IP/ATM/SDH/WDM. Clearly, operating a network composed of many layers is not a simplest and cheapest endeavor, and that is why in so called IP over WDM initiative [IW01][IW02], an objective is to make a space between uppermost and lowermost layers as thin as possible.

In short, intelligence of intermediate layers in IP/WDM networks is pushed both upwards to the IP layer, and downwards to the WDM layer.

2.3. Mathematical Description of the Optical Transport Network

In a highly abstract view, an optical transport network (OTN) is composed of optical links and optical nodes. An example of optical network is shown in Figure 2.2. In the work, nodes are sometimes referred to as WDMPoPs, or WDM capable points of presence. Besides being capable of routing different types of traffic, this also implies that they are capable of being entry and exit nodes for WDM network clients traffic demands.

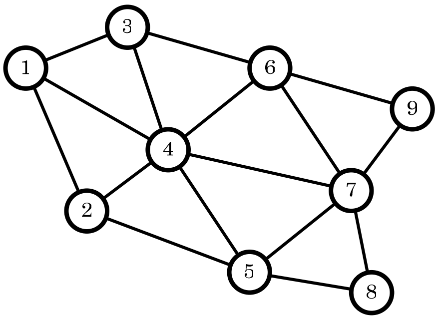


Figure 2.2. – An example network

In terms of graph theory, topology of an OTN G is described as undirected graph, composed of set of nodes (vertices) $\mathbf{V}$ and set of links (edges) $\mathbf{E}$,

$$G = \{\mathbf{V}, \mathbf{E}\} \tag{2.1}$$

$$\mathbf{V} = \{v_i : i \in \{1,...,N_V\}\}, \tag{2.2}$$

$$\mathbf{E} = \{e_j : j \in \{1,...,N_E\}\}, \tag{2.3}$$

where $N_V = |\mathbf{V}|$ and $N_E = |\mathbf{E}|$ are number of nodes and links, respectively. Length of each edge is expressed by the following notation,

$$\{l_j : \forall e_j \in \mathbf{E}\}$$

Each link is composed of number of fibers, each of which could be used for transmission in both directions. Direction is determined at design time.

Set of fibers on a link e_j is denoted as,

$$\boldsymbol{\varphi}_j = \left\{ \phi_{jk} : e_j \in \mathbf{E}, k \in \left\{1, \ldots, \left|\boldsymbol{\varphi}_j\right|\right\} \right\}. \tag{2.4}$$

On each fiber a number of wavelength channels (or just wavelengths) are available. In general, a number of wavelengths can vary from fiber to fiber. A wavelength channel is denoted as,

$$\left\{ \lambda_{jkl} : e_j \in \mathbf{E}, \phi_{jk} \in \boldsymbol{\varphi}_j, k = 1, \ldots, \left|\boldsymbol{\varphi}_j\right| \right\}. \tag{2.5}$$

A set of wavelengths available on a fiber ϕ_{jk} is denoted as,

$$\boldsymbol{\lambda}_{jk} = \left\{ \lambda_{jkl} : \phi_{jk} \in \boldsymbol{\varphi}_j, e_j \in \mathbf{E}, l \in \left\{1, \ldots, \left|\boldsymbol{\lambda}_{jk}\right|\right\} \right\}. \tag{2.6}$$

In the expression above, $\left|\boldsymbol{\lambda}_{jk}\right|$ represents number of wavelength channels on fiber ϕ_{jk}, associated to the corresponding link e_j. In the design process it is useful to make an approximation that all fibers in the network carry the same number of wavelength channels,

$$\left|\boldsymbol{\lambda}_{jk}\right| = N_\lambda \text{ for } \forall \phi_{jk} \in e_j, \forall e_j \in \mathbf{E}. \tag{2.7}$$

Some practical values for N_λ are 4, 8, 16, 32, 40, 64, 80, 100 etc.

A wavelength channel group (λG) contains group of wavelength channels (λ) and is denoted as,

$$\lambda G_{jkmn} = \left\{ \lambda_{jkl} : e_j \in \mathbf{E}, \phi_{jk} \in \boldsymbol{\varphi}_j, k = 1, \ldots, \left|\boldsymbol{\varphi}_j\right|, l = m, \ldots, n \right\},$$

$$\lambda G_{jkmn} \subset \boldsymbol{\lambda}_{jk}. \tag{2.8}$$

Note that definition assumes continuity of wavelength channels contained within a wavelength channel group. If the discontinuity of wavelengths contained in a wavelength channel group is allowed, then we would write,

$$\lambda G_{jkg} = \left\{ \lambda_{jkl} : \lambda_{jkl} \in \boldsymbol{\lambda}_{jk}, \lambda_{jkl} \in \lambda G_{jkg} \right\}. \tag{2.9}$$

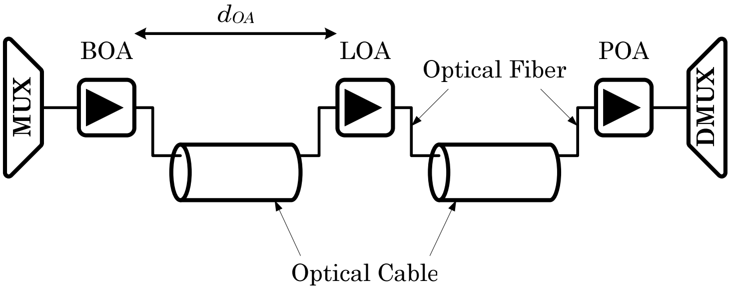


Figure 2.3. – Model of an optical link

Figure 2.3 shows a model of optical link assumed in this thesis. We assume that each fiber in an optical link is accompanied by a chain of optical amplifiers. The structure of this chain is;

a.) 1× booster optical amplifier (BOA), immediately after the multiplexer,

b.) 1× optical pre-amplifier (POA), before the de-multiplexer, c.) $N_{LOA,j} = \left\lceil \frac{l_j}{d_{OA}} \right\rceil - 1$ line optical amplifiers, where d_{OA} represents the distance between line optical amplifier.

In addition to optical amplifiers, each optical fiber is also accompanied by a multiplexer on one end, and de-multiplexer on the other.

Path π_{sd} is an ordered sequence of nodes and links; it starts with a node *s*, and ends with a node *d*. After node, a link follows, and vice versa. Thus,

$$\pi_{sd} = \left\{ x_\pi : \begin{array}{c} x_\pi \in \mathbf{E} \text{ or } x_\pi \in \mathbf{V} \\ x_0 = s,\, x_{|\pi_{sd}|} = d \\ \text{if } x_\pi \in \mathbf{E} \text{ then } x_{\pi+1} \in \mathbf{V} \\ \text{if } x_\pi \in \mathbf{V} \text{ then } x_{\pi+1} \in \mathbf{E} \end{array} \right\}. \tag{2.10}$$

Note that the expression allows for an element to appear more than once in the sequence. *Elementary path* is a path in which there are no elements that appear twice.

We assume that two paths, π_{ij} and π_{kl} are independent, if, and only if,

$$x_{\pi_{ij}} \neq x_{\pi_{kl}} \text{ for } \forall x_{\pi_{ij}} \in \pi_{ij} \setminus \{v_i, v_j\} \text{ and } \forall x_{\pi_{kl}} \in \pi_{kl} \setminus \{v_k, v_l\}. \tag{2.11}$$

The independency requirement can be relaxed, so that only dependency in terms of nodes or links is required. Paths will be *link independent* if and only if,

$$x_{\pi_{ij}} \neq x_{\pi_{kl}} \text{ for } \forall x_{\pi_{ij}} : x_{\pi_{ij}} \in \pi_{ij}, x_{\pi_{ij}} \in \mathbf{E} \text{ and } \forall x_{\pi_{kl}} : x_{\pi_{kl}} \in \pi_{kl}, x_{\pi_{kl}} \in \mathbf{E}. \tag{2.12}$$

Paths will be *node independent* if, and only if,

$$x_{\pi_{ij}} \neq x_{\pi_{kl}} \text{ for } \forall x_{\pi_{ij}} : x_{\pi_{ij}} \in \pi_{ij}, x_{\pi_{ij}} \in \mathbf{V}, x_{\pi_{ij}} \neq v_i, x_{\pi_{ij}} \neq v_j \text{ and} \tag{2.13}$$

$$\forall x_{\pi_{kl}} : x_{\pi_{kl}} \in \pi_{kl}, x_{\pi_{kl}} \in \mathbf{V}, x_{\pi_{kl}} \neq v_k, x_{\pi_{kl}} \neq v_l. \tag{2.14}$$

The paths are totally independent if they are both link and node independent.

Cycle is a path in which first and last node are identical,

$$\chi_s = \left\{ x_\chi : \begin{array}{c} x_\chi \in \mathbf{E} \text{ or } x_\chi \in \mathbf{V} \\ x_0 = s,\, x_{|\chi_s|} = s \\ \text{if } x_\chi \in \mathbf{E} \text{ then } x_{\chi+1} \in \mathbf{V} \\ \text{if } x_\chi \in \mathbf{V} \text{ then } x_{\chi+1} \in \mathbf{E} \end{array} \right\}. \tag{2.15}$$

Like in the case of a path, the expression allows for an element to appear more than once in a cycle. On the other hand, definition of an *elementary cycle* does not allow for an element to appear more than once in a cycle, except in the case of starting node *s*.

Finally, *distinct elementary cycle* is a cycle which is not a cyclic permutation of other cycle.

We now define measures for analyzing the quality of a WDM network design.

Total installed number of fibers (TIF).

For each link e_j, a $|\boldsymbol{\varphi}_j|$ number of fibers are installed. Total number of installed fibers is then:

$$TIF = \sum_{j=1}^{N_E} \left| \boldsymbol{\varphi}_j \right| \tag{2.16}$$

TIF determines;

- Number of multiplexers.
- Number of de-multiplexers.
- Number of optical pre-amplifies (POA).
- Number of booster optical amplifiers (BOA).

Total installed fiber length (TIFL).

For each link e_j of length l_j, a $\left|\boldsymbol{\varphi}_j\right|$ number of fibers are installed. Total fiber length is given by the following formula:

$$TIFL = \sum_{j=1}^{N_E} l_j \cdot \left| \boldsymbol{\varphi}_j \right| . \tag{2.17}$$

TIFL determines:

- Number of line optical amplifiers (LOA), in the following way,
  $$N_{LOA} \approx \left\lceil \frac{TIFL}{d_{OA}} \right\rceil - 1$$

Total installed number of wavelength channels (TIWC)

On each link e_j $\left|\boldsymbol{\varphi}_j\right|$ fibers are installed, and on each fiber $\left|\boldsymbol{\lambda}_{jk}\right|$ wavelength channels are accessible,

$$TIWC = \sum_{j=1}^{N_E} \sum_{k=1}^{\left|\boldsymbol{\varphi}_j\right|} \left| \boldsymbol{\lambda}_{jk} \right| . \tag{2.18}$$

Total installed wavelength channel length (TIWCL)

This term could also be referred to as wavelength mileage. Each installed wavelength channel is weighted in terms of the length of its corresponding link,

$$TIWCL = \sum_{j=1}^{N_E} l_j \cdot \left(\sum_{k=1}^{\left|\boldsymbol{\varphi}_j\right|} \left| \boldsymbol{\lambda}_{jk} \right| \right) . \tag{2.19}$$

Terms expressed above reflect the size of the network in terms of available resources in unloaded network, but not in terms of resource usage efficiency. Network resources are used by wavelength paths, or lightpaths. A lightpath is a concatenation of wavelength channels between end nodes. Concatenation is realized in optical nodes either passively, by connectors or fusion splices, or actively, by means of optical space (and/or wavelength) switches.

A *lightpath* between nodes *s* and *d* is described as follows,

$$\Lambda_{sd} = \left\{ \lambda_{jkl} : \text{for } \forall e_j \in \pi_{sd}, \phi_{jk} \in e_j \right\} , \tag{2.20}$$

where π_{sd} is a path between pair of nodes *s* and *d*, composed of nodes and links. A lightpath is unidirectional end-to-end communication.

If wavelength conversion is not possible in OTN, then a lightpath uses the same wavelength on all optical links,

$$\lambda_{jkl} = \lambda \text{ for } \forall e_j \in \pi_{sd}, \phi_{jk} \in e_j . \tag{2.21}$$

Note though, that such restrictions are not imposed on the selection of fiber. In this scenario, a lightpath is called wavelength path (WP), and OTN is sometimes referred to as WP OTN.

If OTN possesses capability of wavelength conversion, then a lightpath is generally allocated to different wavelengths along its path. In this case, lightpath is called virtual wavelength path (VWP), and OTN is termed VWP OTN.

Lightcycle is defined as,

$$\Theta_s = \left\{ \lambda_{jkl} : \text{for } \forall e_j \in \chi_s, \phi_{jk} \in e_j \right\}, \tag{2.22}$$

where χ_s is a cycle starting from node *s*, composed of nodes and links.

If wavelength conversion is not possible in OTN, then a lightcycle is allocated to the same wavelength on all optical links,

$$\lambda_{jkl} = \lambda \text{ for } \forall e_j \in \chi_s, \phi_{jk} \in e_j . \tag{2.23}$$

In an OTN, a number of lightpaths is established between a pair of nodes. The number is indicated in the traffic demand matrix. The traffic demand matrix is denoted,

$$\mathbf{N\Lambda} = \left| N\Lambda_{sd} \right| . \tag{2.24}$$

In the thesis we assume symmetrical traffic demands,

$$N\Lambda_{sd} = N\Lambda_{ds} \text{ for } \forall (s,d) \in \mathbf{V}, s \neq d .$$

Lightpath *j* between nodes *s* and *d* is denoted as,

$$\Lambda_{sd,j} : s,d \in V, s \neq d, j = 1,\ldots,N\Lambda_{sd} . \tag{2.25}$$

In WP OTN lightpaths are defined through a process called *Routing and Wavelength Assignment* (RWA) [DE10][DE12][DE13]. In VWP OTN, only process of routing is used to define lightpaths. The result of the process is variable,

$$\mathbf{Xr} = \left\{ \mathbf{Xr}_{jkl} = \left\{ \Lambda_{sd,j} : \lambda_{jkl} \in \Lambda_{sd,j} \right\} \right\} . \tag{2.26}$$

Definition allows for a more lightpaths to share the same wavelength channel λ_{jkl}, but this is only possible if two lightpaths are disjoint, i.e. their activation can not happen at the same time. Note the difference between terms independent and disjoint.

Utilization efficiency of a fiber ϕ_{jk} is defined as,

$$FUE_{jk} = \frac{\sum\limits_{\forall \lambda_{jkl} \in \phi_{jk}} \left| \mathbf{Xr}_{jkl} \right|}{\left| \boldsymbol{\lambda}_{jk} \right|} . \tag{2.27}$$

Link utilization efficiency is defined as,

$$LUE_j = \frac{\sum\limits_{\forall \phi_{jk} \in \boldsymbol{\varphi}_j} \sum\limits_{\forall \lambda_{jkl} \in \phi_{jk}} \left| \mathbf{Xr}_{jkl} \right|}{\sum\limits_{\forall \phi_{jk} \in \boldsymbol{\varphi}_j} \left| \boldsymbol{\lambda}_{jk} \right|}. \tag{2.28}$$

In special case, when the number of wavelengths on each fiber in network is the same, (2.18) becomes,

$$LUE_j = \frac{\sum\limits_{\forall \phi_{jk} \in \boldsymbol{\varphi}_j} FUE_{jk}}{\left| \boldsymbol{\varphi}_j \right|}. \tag{2.29}$$

Finally, overall network utilization efficiency is,

$$NUE = \frac{\sum\limits_{\forall e_j \in \mathbf{E}} \sum\limits_{\forall \phi_{jk} \in \boldsymbol{\varphi}_j} FUE_{jk}}{\sum\limits_{\forall e_j \in \mathbf{E}} \left| \boldsymbol{\varphi}_j \right|}. \tag{2.30}$$

In order to evaluate given network design, measures (2.16), (2.17), (2.18), and (2.19) are used. These measures are in close relationship to installation costs of a network.

On the other hand, measures (2.27), (2.28), (2.29), and (2.30) incorporate ability of a telecomm operator to earn money from a considered network design in a efficient manner, due to the fact that utilization of the installed network resources is taken into account.

2.4. Switching Paradigms

There are three basic switching schemes in the all-optical networks. Sometimes, a term switching paradigm is used. These are namely optical circuit switching (OCS), optical packet switching (OPS), and optical burst switching (OBS).

2.4.1. Optical Circuit Switching

OCS is the most mature switching scheme and only one used in production optical networks. One of the reasons for that being true lies in the fact that it is the simplest of the switching paradigms. In such switching paradigm, as illustrated in the Figure 2.1, a lightpath is established between source and destination nodes. This is achieved through use of free wavelength channels along the chosen path between pair of nodes.

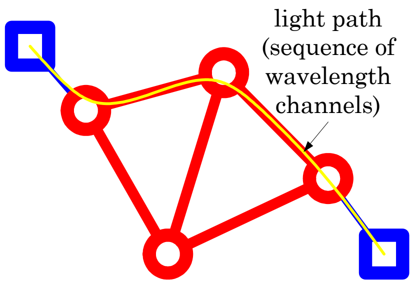


Figure 2.4. – Wavelength paths (lightpaths) in OCS

Thus, ending nodes have at their disposal lightpath, a concept similar to pure optical fiber, and can make their own decision on the speed and protocol that will be used for communication. We usually say that such communication channel is both bit-rate and protocol transparent. For example, source and destination nodes can be terabit routers with STM-64/OC-192 network interface cards at speed of 10 $Gbit/s$ [IW03] [IW04]. On other lightpath two ATM switches could communicate at speed of 622 $Mbit/s$. In the case of OCS, this is true only for bit-rates (speeds) up to some limit value, which we denote in this thesis as full wavelength capacity (FWC). FWC is determined by the techniques (modulation, dispersion compensation, pulse shaping and other) and equipment (i.e. optical amplifiers, wavelength converters) used at the physical level. At this point, one can make difference between networks that make use of wavelength converters and those that do not. In the latter case, the lightpath uses the same wavelength on all links it passes through, and in this case we speak of wavelength path (WP) scheme. In the first case, lightpath generally changes its wavelength on links it passes through, and thus we use term virtual wavelength path (VWP).

2.4.2. Optical Packet Switching

On the other side of the switching paradigm spectrum one finds optical packet switching [BS01] [BS02] [PS02] [PS01] [PS03]. The concept of this switching paradigm is similar to that of classical copper packet switched networks, such as IP, and is illustrated in the Figure 2.5. At the entrance to optical network, information is placed into optical packets. An optical header containing routing information is added to optical packet, and such self-contained entity is sent into network. Nodes are responsible for reading optical headers, and according to the content of a header, for making routing decisions.

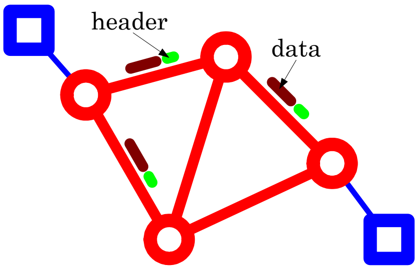


Figure 2.5. – The concept of optical packet switching

Advantage of this switching paradigm is in the fact that nowadays the dominant protocol for transferring data is IP, based on packets/datagrams. Thus, mapping of IP packets into optical domain should be simple and efficient. Potential problems are related to the content resolution schemes at the photonic layer, within optical packet switching nodes. A content resolution in the photonic domain could be realized in space (space division switches), wavelength (wavelength converters), or time domain (optical memories). Furthermore, optical memories are usually implemented as fiber delay loops (FDL), which leads to a number of transmission related problems (signal degradation in FDLs). In short, photonic devices that can be used for content resolution are at the time of writing of the thesis still not mature and not used for commercial purposes.

There are several laboratory and experimental implementations of optical packet switching architectures. Some of them are;

- ATMOS (ATM *Optical Switching*) [PS06][PS07],
- KEOPS (*KEys to Optical Packet Switching*) [PS08],
- WASPNET (*WAvelength Switched Packet NETwork*) [PS09],
- DAVID (*DAta and Voice Integration over DWDM*) [PS10].

In [PS06] an overview of architectures for optical packet switching networks is presented. Performance analysis of different contention resolution schemes, node and network architectures, is presented.

2.4.3. Optical Burst Switching

Problems with the implementation of optical memory led to the development of the concept termed optical burst switching (OBS) [PS04] [BS03] [PS03]. The concept is an old one, conceptually developed in the 80-ies of the 20th century. Principle of OBS is illustrated in Figure 2.6.

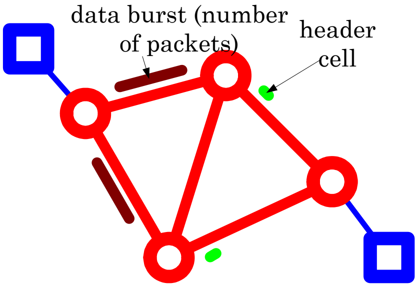


Figure 2.6. – A concept of optical burst switching

A number of packets make single burst. The functioning of OBS is based on the unidirectional resource reservation, in which, before sending a burst of data, a header cell is sent through the network. Unlike optical packet switching, a header cell is traveling alone, and contains all the information necessary so that the optical burst nodes can make appropriate switching just before the burst arrives at the node. For example, header cell carries information about the length of the burst and delay between the header cell and corresponding burst. After header cell is processed, optical burst switching node will have enough time to make necessary scheduling, and prepare appropriate switching for a moment when burst itself will arrive at the input of the node. Hence, the use of optical buffering could be kept at the minimum possible level.

There are two most cited signaling protocols used in OBS. Figure 2.7 shows *Just In Time* (JIT) [BS04] protocol. Burst is sent to the network after a time delay, which is calculated as time needed for a header cell to notify all the nodes on the way towards destination ($t_{protocol}$), and time to do the switching in nodes ($t_{switching}$). Burst does not wait for the confirmation.

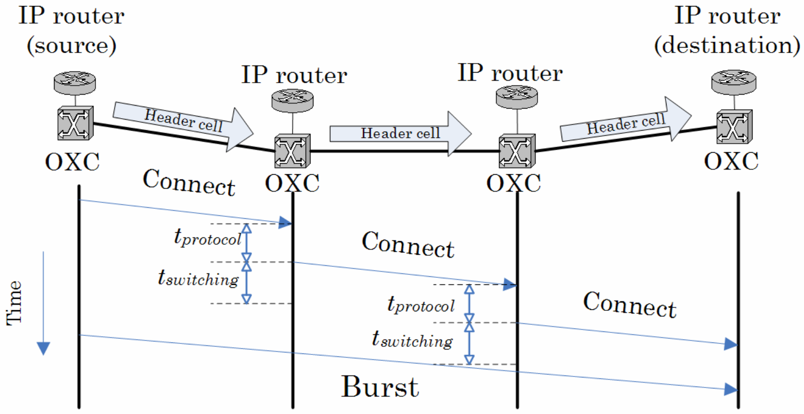


Figure 2.7. – Connection establishment in OBS

Another example of the signaling protocol proposed for OBS networks is *Just Enough Time* (JET) [BS03]. Main characteristic of this protocol is delayed reservation of network resources.

Within the OBS, different resource reservation and scheduling techniques can be used in order to prepare burst switching node for the arrival of a burst. Examples of such algorithms are;

- *Horizon Scheduling* (HS) [BS05],
- First Fit Unscheduled Channel (FFUC) [BS09],
- Latest Available Unscheduled Channel (LAUC) [BS06],
- Generalized LAUC with Void Filling (G-LAUC-VF) [BS07],
- First Arrival First Assignment – Void Filling (FAFA-VF) [BS08].

In [BS09], an overview of optical burst switching architectures is given. Performance analysis of signaling, scheduling and contention resolution techniques is also presented.

2.4.4. Comparison of Switching Paradigms

Table 2.1 briefly summarizes main characteristics of switching paradigms. Signaling issues are presented in Table 2.2.

Table 2.1. – Comparison of switching paradigms

	Granularity	Switching time	Network utilization	Complexity
OCS	high (wavelength channel)	*ms*	low	low
OBS	medium (burst)	µ*s*	medium	medium
OPS	small (packet)	*ns*	high	high

Table 2.2. – Comparison of signaling in switching paradigms

	Signaling Time	Ratio between control information and data	In-band signaling
OCS	high	low	no
OBS	medium	low	no
OPS	low	high	yes

2.5. Protection and Restoration Paradigms

In addition to type of service requested from the all-optical network, a user could request for high(er) resilience of his demands. By the term *resilience* we mean higher probability of a service being available in the event of a failure. In some cases, it would be in the interest of the owner of an all-optical network, i.e. network operator, to provide higher level of resilience to some (or all) service requests from higher layers, since the outage results in loss of revenue.

The techniques for achieving high resilience of a network are commonly known as protection & restoration (P&R) paradigms. Generally, in the P&R techniques, in addition to working transport entities, used normally, one or more backup transport entities are defined for the service provided by the optical transport network. P&R paradigm specifies actions that will be taken during the time of service provisioning, and in case of working transport entity failure during the service life cycle.

Discussion in this chapter is given in the context of transport entities within circuit switching paradigm, but could be extended to other switching paradigms as well. This is the reason why we use a generic term of transport entity, which is defined as a fundamental unit of a transport layer. For example, in the context of GMPLS [CM02], a concept of label switched path (LSP) is used to denote a connection between two interfaces of the same type. These interfaces can be, for example, wavelength, or packet capable, and hence could refer to a wavelength path (or lightpath) or packet related connection (packet route). The GMPLS is discussed in the section 2.7.1. Formal definition of transport entities is given in the chapter 3.

The classification of P&R paradigms presented in this section is based on different technologies, such as SDH [RI01][SR07][SR08], WDM [SR01] [SR02] [SR03] [SR04] [SR06], GMPLS [CM02] [CM15] [CM16] and MPLS [SR05]. The goal was to define generic P&R schemes applicable to different switching and topological paradigms. Note that topological and switching paradigms define additional specifics to the generic P&R techniques and schemes presented here.

The classification of P&R paradigms is made in terms of following criterions;

- Backup transport entity provisioning time, relative to the service life cycle. By the term provisioning we mean routing of transport entities, working or backup. The criterion divides P&R techniques to;
    - Protection – provisioning actions take place only at the beginning of the transport entity life cycle. If a failure occurs, backup entity will be used to carry traffic, but no additional provisioning actions will take place. If another failure occurs on the backup transport entity, while primary is still in the failure state, service provided by the transport entity will be unavailable.
    - Restoration – provisioning actions take place at the beginning and during the service life cycle. During the service life cycle, provisioning actions generally take place after a failure occurs, but in order to have restoration as fast as possible, backup transport entities can be calculated after each failure.
- Backup transport entity provisioning time, relative to the moment of failure;
    - Proactive – pre-calculation of backup transport entities is made before the failure occurs, for example, during provisioning, or after the activation of pre-calculated backup transport entity. Note that protection is by the definition proactive.
    - Reactive – backup transport entities are determined only after failure affects the working transport entity. This is the slowest P&R scheme in terms of time required to activate backup transport entity.
- Dedication of the backup transport entity to the working. In this regard, we have;
    - Dedicated – In this P&R technique there is one-to-one mapping between working and backup transport entity.
    - Shared – In this P&R scheme, generally, M backup transport entities are shared by N working. Special cases are 1:1 and 1:N. The general case is M:N.
- Level of switching action, i.e. nodes that take switching actions;

  - Path or end-to-end – End nodes take switching actions. This means that failure needs to propagate to the end nodes.
  - Span – Intermediate nodes, closest to the place of failure, take switching actions. In general, this scheme will result in faster failure detection than the path scheme.
- Directionality;
  - Bidirectional – Transport entities for both directions share the same fate. In the case of failure that affects either direction, both directions will be rerouted to their respective backup transport entities.
  - Unidirectional – P&R is applied independently to each direction of a communication.
- Action after the failure have been resolved;
  - Revertive – Traffic will be rerouted over working transport entities. This will possibly result in additional instabilities.
  - Non-revertive – Basically, working and backup transport entities switch their roles after the failure occurs and affected traffic has been rerouted over the backup transport entity. This will not cause any additional transients in the network, but traffic routing will be (possibly) suboptimal.

Table 2.3 shows all allowable combinations between different P&R schemes. The table can be represented as a graph. The illustration of the classification in Figure 2.8 represents the sub-set of this graph, with the most interesting combinations.

Table 2.3. – Relations between P&R schemes

	Protection	Restoration	Proactive	Reactive	Dedicated	Shared	Path	Span	Bi-directional	Uni-directional	Revertive	Non-revertive
Protection			✓		✓	✓	✓	✓	✓	✓	✓	
Restoration			✓	✓		✓	✓	✓	✓	✓	✓	✓
Proactive					✓	✓	✓	✓	✓	✓	✓	✓
Reactive					✓	✓	✓	✓	✓	✓	✓	✓
Dedicated							✓	✓	✓	✓	✓	✓
Shared							✓	✓	✓	✓	✓	✓
Path									✓	✓	✓	✓
Span									✓	✓	✓	✓
Bi-directional											✓	✓
Uni-directional											✓	✓

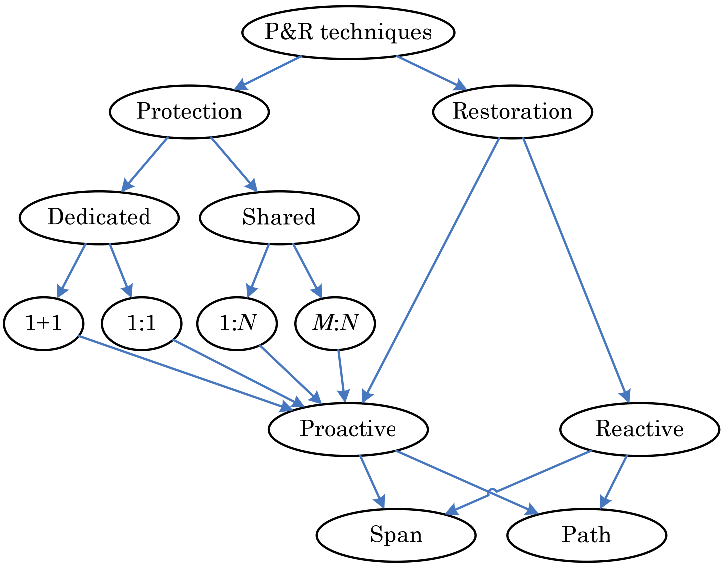


Figure 2.8. – Classification of P&R paradigms

Protection is by the definition proactive way of increasing resilience in networks. Working transport entities have pre-assigned backup transport entities. An example of transport entities in this context are wavelength channels and lightpaths.

Protection can be further divided into dedicated (1+1, 1:1, Figure 2.9) and shared (1:*N*, *M*:*N*). In the 1:1 protection scheme, in a regular case, when there are no failures on the primary, backup transport entities could be used to carry preemptive low priority traffic. In the GMPLS context, such traffic is called extra traffic [CM15].

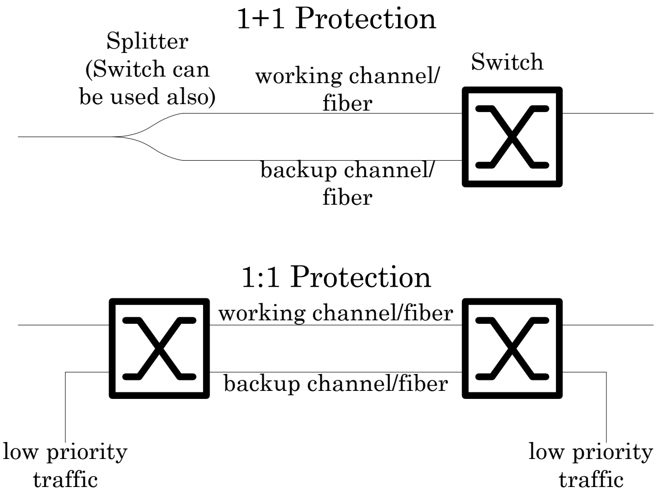


Figure 2.9. – 1+1 and 1:1 Protection

The principle of shared protection is illustrated in Figure 2.10. For a set of *N* working transport entities, one backup transport entity is assigned. The backup transport entity can be used to carry low priority preemptive traffic in the case of failure absence in the network.

In contrast to protection, restoration is usually viewed as a reactive mechanism in which transport entities are rerouted, or restored onto newly determined network resources after the failure have been detected. In real networks backup transport entities can be also predetermined, so one can speak about proactive and reactive restoration schemes.

In general, protection is viewed as a high speed scheme, since in 1+1 protection information (signal) can be sent on both working and backup transport entities, while restoration, beside failure detection and notification, usually requires provisioning of new resources, and reconfiguration of network elements. On the other hand, restoration uses network resources more efficiently.

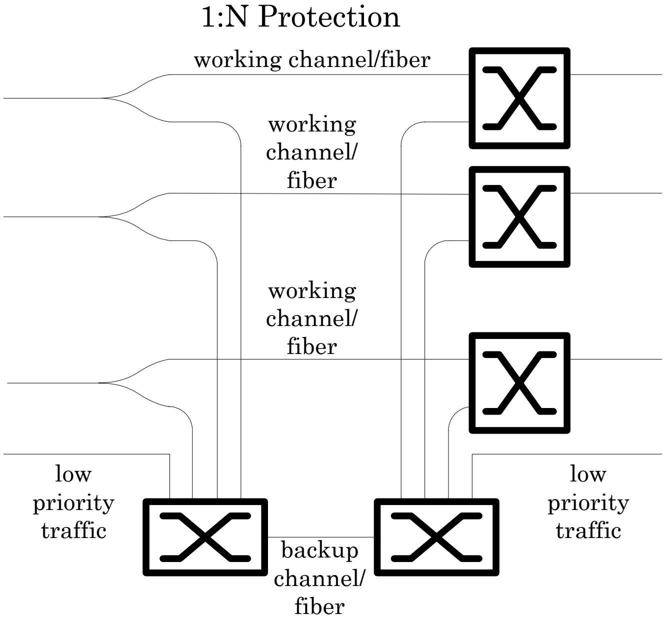


Figure 2.10. – Shared protection (1:N)

The difference between protection and restoration can be also defined in terms of service provisioning time. In the protection, during service provisioning, backup transport entities are calculated. The protection paradigm defines actions to be taken after failure occurs, but additional provisioning after the failure occurs will not take place. Thus, if backup transport entity fails, and working is still not repaired, the service will be unavailable.

In case of restoration, backup transport entities are usually provisioned during the process of service provisioning. For example, we can speak about the 1:1 restoration, in contrast to 1:1 protection, in which working and backup transport entities are provisioned at the time of service provisioning. Similar to 1:1 protection, in normal conditions (without failure) backup transport entities can be used to carry extra traffic. After the failure on primary transport entity occurs, traffic will be switched onto backup transport entity, possibly resulting in loss of extra traffic. Up to that point in service life cycle, behavior of 1:1 protection and restoration are the same. In 1:1 protection, no additional provisioning actions will be taken, while in 1:1 restoration, new backup transport entity will be computed.

Both protection and restoration can be applied to optical multiplex section layer (e.g. whole fiber, or multiplex section), or optical circuit/channel layer (e.g optical channel, or lightpath). Hence one can speak about span (link, OMS) or path (OCh) protection/restoration.

Figure 2.11 shows example of link protection. On each WDM link several fibers are used as backup ones. If, for example fiber on link *A-B* fails, all wavelengths are automatically rerouted onto backup fibers on links *A-C* and *C-B*. Since decision of switching is made locally, e.g. at nodes *A* and *B*, which are closest to the failure, it is clearly the fastest P&R scheme in terms of service restoration times. On the left side of the figure shared version of the link protection is depicted. This scheme will not work for the simultaneous failures of links *A-B* and *B-D*.

Figure 2.12 illustrates path protection. Two working lightpaths are shown, w_1 and w_2, with their corresponding backup lightpaths b_1 and b_2. In the case of failure on any of the network elements w_1 is passing through, lightpath is switched to the b_1, either automatically, if the protection is used, or in the process of restoration. The figure shows 1+1 path protection, since backup lightpaths b_1 and b_2 do not share wavelength.

It is possible and even more efficient in terms of network resources utilization, that backup lightpaths b_1 and b_2 on link *B-D* use the same wavelength. Such network would still survive any single link failure, since w_1 and w_2 do not pass through same optical links, and thus no single failure can affect both of them simultaneously.

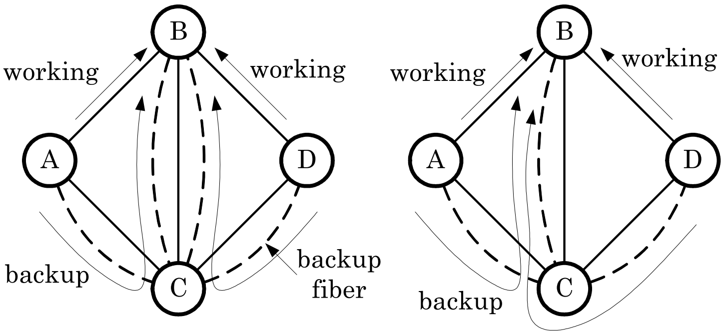


Figure 2.11. – Link protection/restoration

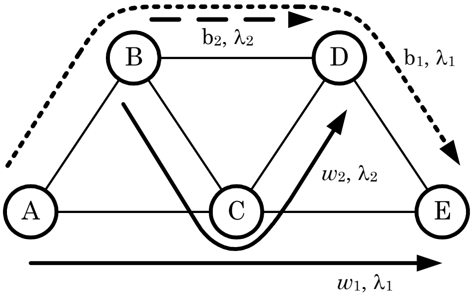


Figure 2.12. – Path protection/restoration

Clearly, in terms of restoration times, the best solution is 1+1 span protection, with 1+1 path protection being slightly slower. On the other hand, 1:1 shared path protection combines high speed of protection with the efficient use of network resources.

2.6. Topological Paradigms

In the work, term topological paradigm is used in the context of different routing patterns, and their ability to exploit given topology of the OTN. Thus, a topological paradigm defines rules of traffic routing and protection to a certain extent. For example, a rule that routes lightpath over a shortest path in a given network topology can be accredited to the mesh topological paradigm. In some cases this rules will be more stringent than in others.

The choice of topological paradigm is one of the first in the process of design of optical network.

We consider following topological paradigms;

- Ring,
- Mesh, and
- p-Cycles

2.6.1. Ring Networks

In general, WDM ring protection schemes are developed from the protection schemes in mature SDH technology. Hence, instead of having SDH self-healing rings (SHR), in WDM ring networks one has WDM self-healing rings, or WSHR. Basically, there are four main WSHR techniques.

Dedicated path switched WSHR (DP-WSHR, Figure 2.13), in the literature also known as optical unidirectional path-switched ring (OUPSR), is equivalent to dedicated path protection in mesh networks. DP-WSHR restoration is fast (on the order of a *ms*, or fraction of a *ms*), but the total protection wavelength mileage is equal or even larger than that required for in other ring protection schemes.

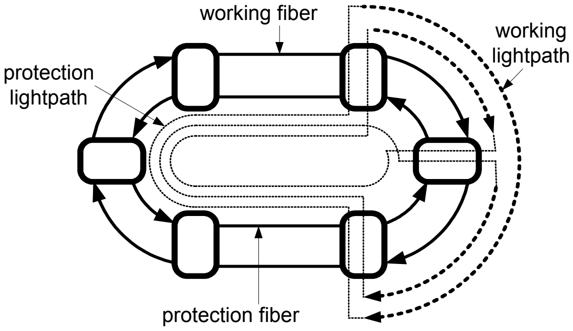


Figure 2.13. – DP-WSHR (OCh/DPRing), non loop-back

Optical unidirectional line-switched ring (OULSR), or dedicated line switched WSHR (DL-WSHR) is similar to DP-WSHR in that it utilizes two counter-rotating fibers, one for working and another for protection lightpaths. The difference is that all the lightpaths passing through failed line/fiber are jointly switched onto protection line/fiber. With respect to DP-WSHR total wavelength mileage is the same [SR03], but due to its line switching, less expensive devices are employed, while achieving same restoration times.

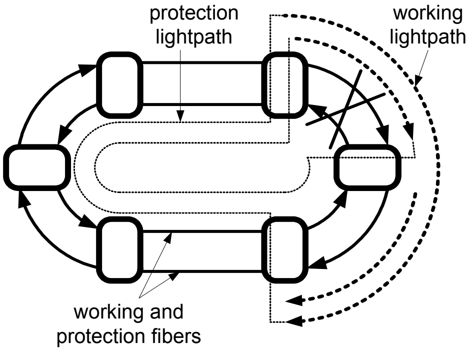


Figure 2.14. – SP-WSHR (OCh/SPRing), non loop-back

In shared path WSHR (SP-WSHR, Figure 2.14), also termed optical bidirectional path-switched ring (OBPSR), working lightpaths are switched to their corresponding protection lightpaths at the source node. Thus, traffic reaches destination node only along the protection lightpath (non loop-back switching). This technique is the most efficient among WSHR protection techniques, in terms of network resources utilization [SR03], but on the other hand requires complex control. As a consequence, restoration times are relatively high [SR03].

Finally, bidirectional shared line-switched WSHR (SL-WSHR, Figure 2.15) can be implemented by either two or four fibers (O-2F/BLSR, O-4F/BLSR). Working and protection lightpaths may be carried using both directions of propagation. This technique implements so called loop-back switching. At the one end of failed link, all working lightpaths are switched to the protection wavelengths of the counter-rotating ring. When they reach other failure end they are looped back onto their original working lightpaths.

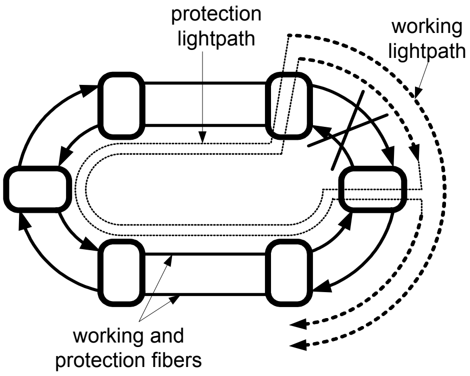


Figure 2.15. – SL-WSHR (OMS/SPRing), loop-back

The SL-WSHR scheme is simple and fast (restoration times in order of tens of *ms* [SR03]).

2.6.2. Mesh Networks

In this thesis term "mesh networks" refers to the ability of the rerouting mechanism to exploit an arbitrary topology in a mesh-like (as opposed to ring-like) way through diverse routing. It does not imply a full mesh graph topology or a regular mesh or hypercube interconnection pattern.

In general, working lightpaths are routed over mesh networks on a shortest path basis. We divide mesh networks according to their capability to respond to network failures. We consider following options:

- No protection.
- 1+1 protection.
- 1:1 restoration, and extension to general 1:*N* restoration.
- Span restoration.
- Dynamic restoration or Shortest Path after Failure restoration (SPAF).

2.6.2.1. No Protection

In this scenario, lightpaths are routed over a single path and no guarantees are provided whatsoever in case failure occurs on any of the network elements that the lightpath passes over (Figure 2.16).

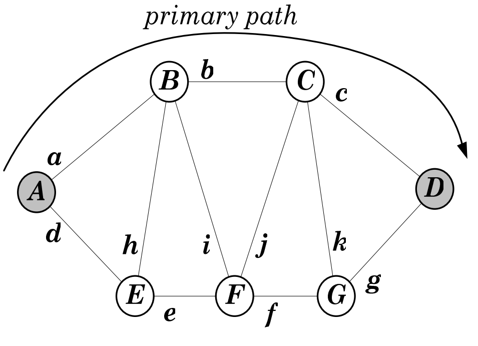


Figure 2.16. – Routing of a shortest path in a no protection case

In the simplest case, lightpaths are simply routed over shortest paths. An alternative is to calculate *k* shortest paths to be used as candidates in the optimization process. In this way, optimal routing in terms of network utilization or load balancing, can be achieved.

2.6.2.2. 1+1 Protection

The 1+1 protection belongs to *dedicated protection architectures*. One spare lightpath is used for the protection of one working lightpath. There are two possibilities of using this protection scenario. In one, the traffic is transmitted on both the working and the spare lightpath at the same time. In this case there is no need for switching. In the second, the traffic is transmitted on the spare path only if the working path is faulty. In this case the switching is necessary on transmitter and receiver side. The switching could be done in electrical or optical domain by using simple switches, 1×2 at transmitter and 2×1 at receiver side. In both cases the same protection transport entity is reserved. Transmission capacities (costs) of the network are at least doubled for 1+1 protection scenario as compared to the network without protection.

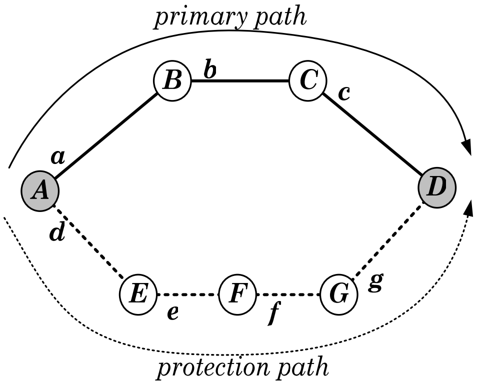


Figure 2.17. – 1+1 protection principle

2.6.2.3. 1:1 Restoration

Each working lightpath, used in fault-free condition, has at least one protection lightpath, placed onto a path that is link and/or node independent with the path onto which working lightpath is placed (Figure 2.18). The so called spare or protection path is loaded by traffic of the primary lightpath only in the case if the primary lightpath is faulty. The primary and its spare path are usually selected as the first shortest path and the second shortest path respectively. Optimized routing can also be used in order to balance the network traffic and improve utilization of transmission resources. In this case a primary and its spare path are chosen among a set of pair paths that are not necessarily the shortest ones.

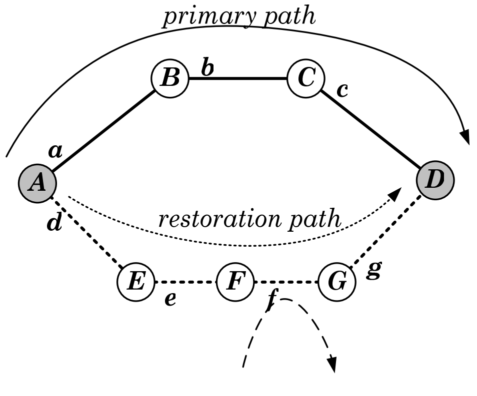


Figure 2.18. – 1:1 restoration principle

The spare capacity of stand-by path can be shared by more than one primary path (for example, two restoration paths on a link *f* between nodes *F* and *G*), but not at the same time. The utilization of transmission resources is better as compared to 1+1 protection, but the traffic routing has to be done in optical cross-connects using active optical switching modules.

1:1 restoration could be generalized into 1:*N* restoration, in which *N* working lightpaths use same protection lightpath. If survivability in case of single failure is required, then all lightpaths, both protection and spare, need to be placed on paths that are independent. Figure 2.19 illustrates this scenario.

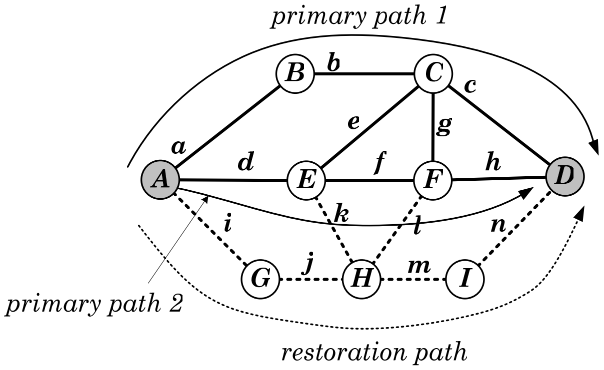


Figure 2.19. –1:*N* restoration principle

2.6.2.4. Span Restoration

In this scenario (Figure 2.20), the restoration is done locally, between two adjacent nodes spanning the faulty link. All optical paths traversing the link in normal condition are re-routed to the spare path, the shortest between the nodes. From the management point of view, this switching scheme is the simplest, because it can be managed locally. The cost of the hardware needed in this scenario is almost doubled in comparison to the scenario without any protection.

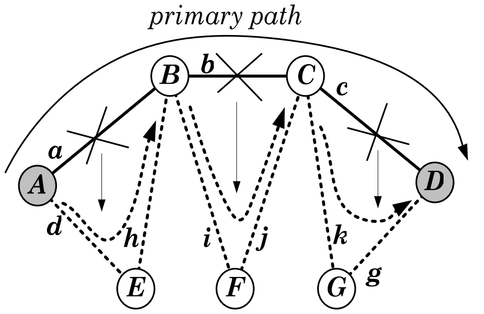


Figure 2.20. – Span restoration principle

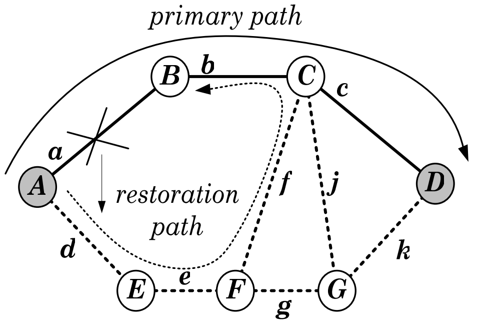


Figure 2.21. – Problem with span restoration

As a consequence of routing mechanism, within restoration path spanning faulty link, a set of links could be used twice: this is the case where the set of links is part of a primary path and restoration route between two nodes directly connect by failed link. Figure 2.21 shows an illustration of this issue: a span restoration between nodes *A* and *B* uses link *b*, which is also used in primary path.

2.6.2.5. Dynamic Restoration

This type of restoration, called also *shortest path after failure* (*SPAF*), searches for the shortest path between source and destination nodes, skipping the failed optical network element, link or node. The primary path and its spare paths are not necessarily independent. For each faulty link on the primary path a specific spare path can be assigned (for example: failures f_1 and f_2 on a primary path *A* cause the activation of spare paths $A(f_1)$ and $A(f_2)$ respectively. In this scenario the total spare capacity or total fiber length can be minimized, but the routing and management in the network could be very complex, requiring sophisticated switching elements and procedures.

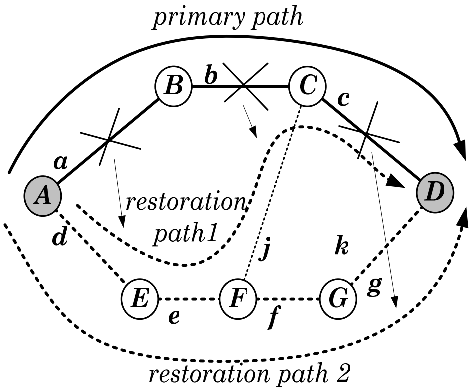


Figure 2.22. – SPAF restoration principle

2.6.3. P-Cycles

The technique of p-cycles is a relatively new approach to survivable network architectures. The concept (or technique) was first introduced in [PC01]. The name has been coined out of term “preconfigured protection cycle”. Basically, a p-cycle is a sequence of capacity units on links that make a cycle in the network topology.

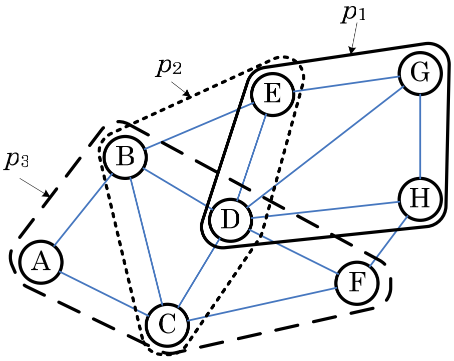


Figure 2.23. – An example of p-Cycles

Figure 2.23 shows three p-cycles, p_1, p_2, and p_3, placed on following links:

$$p_1 = \{E-G, G-H, H-D, D-E\},$$

$$p_2 = \{B-E, E-D, D-C, C-B\},$$

$$p_3 = \{A-B, B-D, D-F, F-C, C-A\}.$$

Note though, that in addition to the list of links, precise address of capacity unit for each link should be specified in order to completely describe the p-cycle. The term “capacity unit” is deliberately used in order to be as general as possible. Capacity unit could for example refer to a SDH lower order tributaries, or, as in WDM network, it could refer to a wavelength channel, or even a fiber. Thus, this concept can be applied to higher layer as well (e.g. SDH or ATM).

In the case of OTN, a p-cycle is a sequence of wavelength channels placed on links that create a cycle in the topology. In the case of WDM network without the possibility of wavelength conversion, wavelength channels composing a p-cycle have the same wavelength. However, in the thesis we assume possibility of wavelength conversion, implying that wavelength channels composing a p-cycle will generally utilize different wavelengths. Furthermore, in the thesis p-cycle will be referred to as a *p-lightcycle*, or just a *lightcycle*.

The concept of p-cycles does not allow for a p-cycle to pass over a link more than once. In other words, a p-cycle is placed onto elementary cycle in a given network topology. Clearly, a p-cycle must comprise of at least three links, but only those links that exist in physical topology (or lower layer topology) are allowed. In the case there are no failures in the network, all p-cycles are closed loops.

In the fundamental paper describing p-cycles [PC01] following definitions are used:

- Link – interconnects two nodes in a WDM network, it is a fiber dedicated to transmission in one direction
- Span, or Duct – comprises all fibers between given pair of nodes.

In this work, instead of link, we use the term capacity unit, or wavelength channel, and instead of span (or duct), we use the term link (or optical link).

2.6.3.1. Principle

We now conceptually explain how p-cycles work and explain reasoning behind syntagm “ring like speed with mesh like efficiency” [PC01].

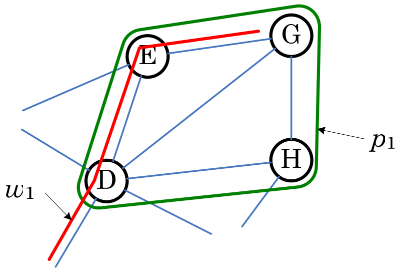


Figure 2.24. – Network segment

Consider a part of the network from Figure 2.23, as shown in Figure 2.24. The figure shows a p-cycle p_1, and a segment of a working lightpath w_1, i.e. a lightpath used to carry traffic in normal conditions, without failures.

Let us now assume that the link *E-D* fails. Remember that capacity of a p-cycle is equal to the capacity of a lightpath. Thus, a p-cycle p_1 can be used to carry traffic for w_1 on a failed link *E-D*. The protection switching corresponds to Figure 2.25.

Only two switching actions are required, and these actions are taken on nodes closest to the failure. Thus, one can have ring-like fast reaction to the failure. So, instead of reaching node E directly, traffic is, through p-cycle, rerouted across nodes H, G and finally E. The traffic continues from node E as previously.

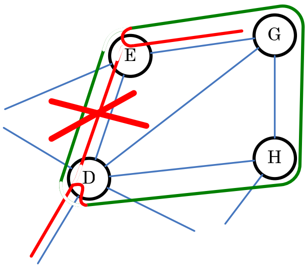


Figure 2.25. – Switching action in a p-cycle example: on cycle link failure

The reaction time depends on the following:

- Link length, l
- Speed of electromagnetic wave in fiber, v_f
- Processing in source and destination node, t_{PROCs}, t_{PROCd}
- Switching times, t_{Xs}, t_{Xd}

Reaction time can be expressed as:

$$t_r = \frac{l}{v_f} + \max\left\{t_{PROCs} + t_{Xs}, t_{PROCd} + t_{Xd}\right\}.$$

It is clear that reaction time will be lower than in mesh topological paradigm, where failure detection is made on an end-to-end basis, i.e., in which failure must propagate through a number of links and nodes.

A p-cycle can also protect working capacity units on other links of a p-cycle. For example, in case of failure on link D-H (see Figure 2.24), a single capacity unit on the link D-H can be protected by the same p-cycle. This means, if a p-cycle is placed onto P links, it can be used to protect, at best, $W = P$ working capacity units. We say at best, because it is possible that there are no working lightpaths routed over some of the p-cycle links, or they are already protected by other p-cycles. To conclude, in order to realize p-cycle routed over P links, a P spare capacity units are required, and at best, a p-cycle can be used for shared protection of $P = W$ working capacity units. In case of a single failure in a network, no traffic will be lost, except for that in transients immediately after failure. Thus, at least 100 % of protection capacity will be required.

We can now state one of the optimization goals when choosing p-cycles: Choose p-cycles in a way that there is a 1 to 1 mapping between a unit of protection capacity, on a p-cycle, and a unit of working capacity.

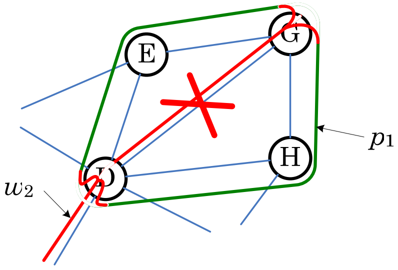


Figure 2.26. – Switching action in a p-cycle example: straddling link failure

We continue our discussion with failure of a link D-G, and working lightpath w_1, as illustrated in Figure 2.26. In this case, protection switching can be accomplished in two possible ways: through the node E (links D-E and E-G), or through the node H (links D-H and H-G).

On the other hand, we can say that 2 units of working capacity on a link D-G can be protected by the p-cycle p_1. Such link is called "straddling span" in the fundamental reference [PC01], or "straddling link" in the thesis. A straddling link connects two nodes in a p-cycle, but is not a part of the p-cycle. Thus, without adding extra spare capacity in the network, already assigned capacity to the p-cycle can be used to protect 2 units of working capacity on links that are straddling to the p-cycle.

If we assume that a p-cycle is placed on P links, and there are S straddling links to that p-cycle in a given topology, then the theoretical maximum of working capacity units that can be protected by the considered p-cycle is,

$$P + 2 \cdot S .$$

Since P also equals to the number of spare capacity units, redundancy, i.e. percentage of extra capacity that is added to the network, for the best case, can be calculated as,

$$Red_{max} = \frac{P}{P + 2 \cdot S} .$$

Further, theoretically speaking, number of straddling links can be 0, and in some cases it is possible to have,

$$\frac{S}{P} > 1 .$$

For example, in a fully meshed network with N nodes, i.e. complete directed graph (CDG), each p-cycle with maximum circumference (N nodes, and $N-1$ links) has following number of straddling links,

$$S_{max} = \binom{N}{2} - N = \frac{N^2 - 3 \cdot N}{2} .$$

Some of the values are illustrated in the Table 2.4.

Table 2.4. – Maximum number of straddling links and redundancy for CDGs

N	3	4	5	6	7
P	3	4	5	6	7
S_{max}	0	2	5	9	14
Red	1	0.5	0.33	0.25	0.2

Redundancy will be lower if we choose p-cycles with higher number of straddling spans. More discussion on p-cycle efficiency is given in [PC02].

Next, we describe generic modeling procedure for networks with p-cycle topological paradigm.

2.6.3.2. Generic Modeling Procedure for P-Cycle Networks

In general, procedure for a p-cycle network design is divided into two steps:

1. Routing of working transport entities.

   In this regard, it is irrelevant what the working transport entities are. They could be lightpaths or logical channels for example, or optical fibers for that matter. The simple routing could use shortest paths, or in a more subtle approach, routing choices for working transport entities could be strongly related to the second step in a design procedure, as we will explain later in the section.

2. Selection of p-cycles out the set of pre-calculated cycle candidates.

   This step should result in full coverage of working capacity units, meaning that each unit of working capacity has its corresponding p-cycle.

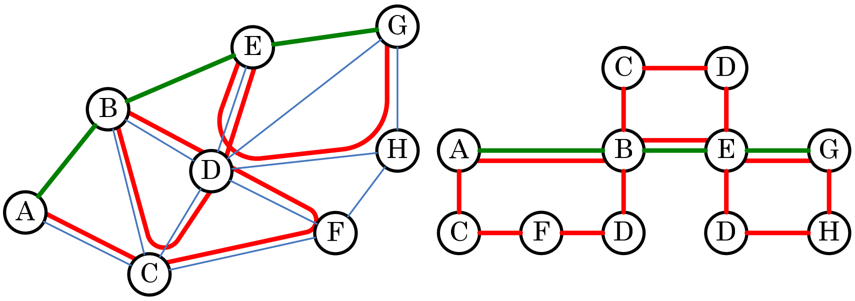


Figure 2.27. – An example of working lightpath and corresponding p-cycles

The left side of Figure 2.27 illustrates an example of lightpath routing between nodes *A* and *G* from a Figure 2.23. Three p-cycles, p_1, p_2 and p_3, are needed in order to protect three units of working capacity, but, as already said, these p-cycles can be used to protect other units of working capacity as well. The right side of the Figure 2.27, the same situation is shown, but from a different perspective. Note that different units of protection (spare) capacity are needed on a link *D-E*, because no sharing is allowed between two p-cycles.

There are three different design scenarios for p-cycle networks, and they are listed and explained below:

1. Optimal design of a network with p-cycles (“green field”), with no capacity constraints, and with optimization goal of network resources and/or redundancy ratio minimization. Thus, there are no constraints on used units of either working or spare capacity on optical links.
2. Optimal routing of traffic demands through optical network with limited capacity on optical links. The goal of this scenario could be twofold. First, if possible, to protect all units of working capacity, and then, if that was achieved, to minimize the redundancy ratio. Second, if it is not possible to protect all of the units of working capacity, the optimization goal would be to maximize the percentage of protected units of working capacity.
3. Optimal routing of single traffic demand. This scenario is interested in the network models with dynamic traffic. As demands are dynamically requested, they should be provisioned using set of available resources. The goal in this case could be, for example, to use as much as possible already configured p-Cycles, and thus, in perspective, to minimize use of protection capacity, and redundancy ratio.

Common to all design scenarios is the pre-computation (or enumeration) of cycles within the topology of a given network. Depending on the scenario, this can be achieved before the design procedure starts, as in the first design case, or after the working transport entities have been routed, as in the second and third case. An example of the algorithm for enumerating all cycles in the network is presented in [GA01]. When enumerating cycles, different criterions could be imposed on candidate cycles. Let p_i be a candidate for p-cycle, some of the possible criterions are:

a.) Number of nodes in p_i should be at least 3,
$|N_v(p_i)| \geq 3$.

b.) Number of nodes in p_i should be less than some amount, (this could be for example 16 in SDH networks),
$|N_v(p_i)| \leq N_{v,max}$.

c.) Length of the p_i should not exceed predefined value,
$l(p_i) = \sum_{\forall e_i : e_i \in p_i} l_i \le l_{p,max}$, where l_i is the length of the link e_i.
For example, this value could be determined by so called optical network transparency length [TL98].

Within designing procedure, several options can be taken into account:

1. Possibility and extent of wavelength conversion. For example, only some of nodes in a network could be capable of wavelength conversion. Concept of MSPN assumes full wavelength conversion capability, meaning that all nodes are capable of any-to-any wavelength conversion.
2. Are working capacity routing and selection of p-cycles done simultaneously? Alternative is, as in [PC03], first to make working capacity routing (or assume one), and then, on the unused network capacity enumerate possible cycles and then make optimal selection of p-cycles according to some predefined criterion.
3. Are p-cycles configured by a network management system [PC03]? An alternative is to use distributed self-organization, as presented in [PC01].
4. Are p-cycles unidirectional or bidirectional? In the case of bidirectional cycles, both directions of the failed unit of working capacity will be rerouted over same length of optical path, and delay will be same for both directions. This assumption also relaxes optimization problem to some degree, since the number of working transport entities (lightpaths) is twice as in the unidirectional case.

We now explain the notion of protection cycle covering. In order to do so, we will use an example network from the Figure 2.28. We assume that working transport entities, in this case lightpath, have been routed already. The numbers along the optical links in the figure represent the number of units of capacity taken by the working lightpaths.

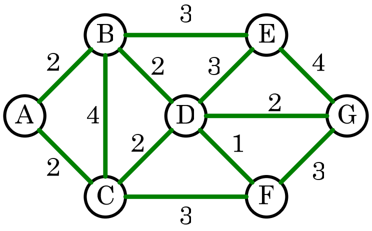


Figure 2.28. – An example network with working capacity units distribution

Furthermore, we assume that there is enough of capacity left in the network, thus we effectively have the first design scenario (unlimited capacity in network).

We assume that following p-cycles are possible in the network:

$$p_1 = \{A-B, B-D, D-C, C-A\},$$

$$p_2 = \{D-E, E-G, G-F, F-D\},$$

$$p_3 = \{B-C, C-D, D-E, E-B\},$$

$$p_4 = \{B-E, E-G, G-F, F-D, D-B\},$$

$$p_5 = \{C-D, D-E, E-G, G-F, F-C\},$$

$$p_6 = \{B-E, E-G, G-F, F-D, D-C, C-B\}.$$

These p-cycles are graphically represented Figure 2.29.

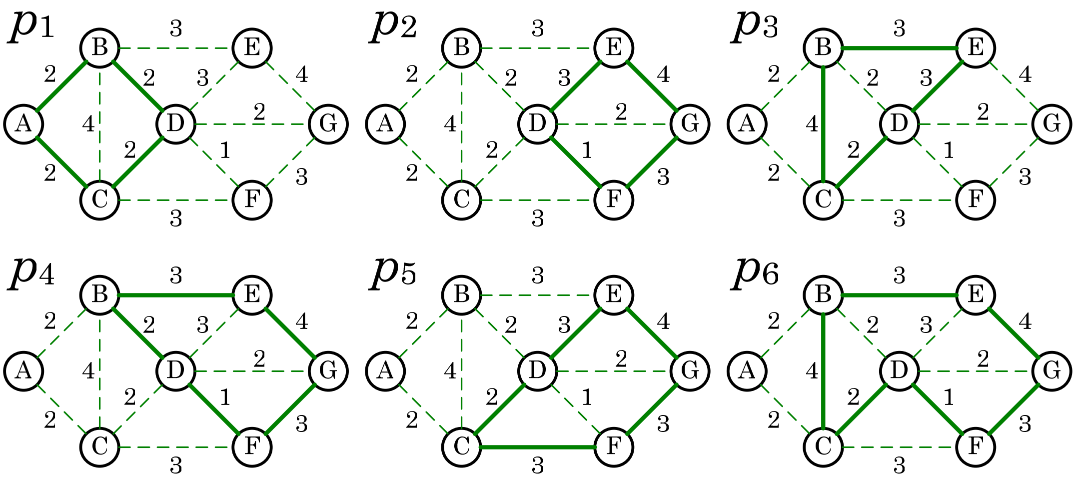


Figure 2.29. – P-Cycles for an example network

Due to the fact that MSPN assumes capability of wavelength conversion on all nodes, it is not necessary to specify wavelength of a p-cycle for each optical link.

If we choose p-cycle p_1, then protection distribution will be as follows (i.e. number of protected units of working capacity):

a.) 1 unit of working capacity on links A-B, B-D, D-C, C-A

b.) 2 units of working capacity on link B-C

Consequently, 6 units of working capacity will be protected by 4 units of protection capacity. Number of unprotected units of working capacity should be decremented by 1 on on-cycle links, while for straddling link the number should be decremented by 2. The distribution of unprotected units of working capacity after choosing p_1 as p-cycle is depicted in Figure 2.30. The reduction in number of unprotected units of working capacity is also illustrated in superscript.

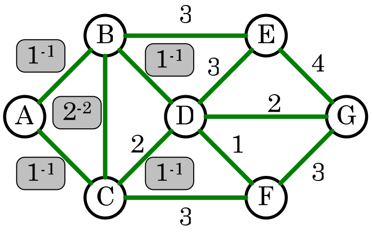


Figure 2.30. – Distribution of unprotected units of working capacity

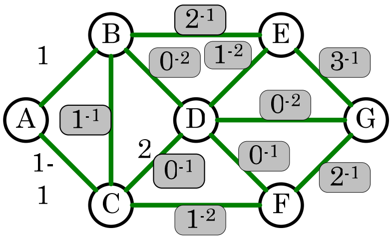


Figure 2.31. – Distribution of unprotected units of working capacity

In the next step we choose a p-cycle p_6. This will result in the distribution of unprotected units of working capacity as shown in Figure 2.31. Clearly, the choice of p_6 was efficient, since number of unprotected units of working capacity was reduced by 13 by using only 6 units of spare capacity. Though p-cycle p_6 could protect 2 units on a link B-D, due to the fact that only 1 unit remained unprotected, total efficiency of the p-cycle covering was reduced from 14/6 to 13/6. The first value is termed in this thesis as potential protection efficiency, while second is termed as actual protection efficiency. Note that the potential protection efficiency could be one of the local goals in the optimization, but it strongly depends on the order of selection of p-cycles. For example, if p_6 was selected before p_1, its actual protection efficiency would be higher (14/6). Clearly, overall efficiency of a solution, in terms of used spare resources, depends not only on the selected p-cycles, but also on the order they were selected to be part of the solution.

Selection of p-cycles should continue until the amount of unprotected units of working capacity equals 0, or until there are available p-cycles (protection resources). Thus, optimization goal can be:

a.) Maximal efficiency, or minimal redundancy, or

b.) Minimal amount of unprotected units of working capacity.

The complexity increases if we assume different resilience classes for traffic demands in the network.

To make discussion more formal we draw a matrix with following dimensions:

$$\mathbf{E} \times \mathbf{P},$$

where **E** is a set of edges, i.e. optical links, and **P** is a set of available p-cycles. The matrix elements will indicate number of units of capacity on an edge e_i that can be protected by a p-cycle p_j. We will denote such element as,

$$Np(e_i, p_j) = Np_{ij}.$$

Clearly, in order to have full coverage of working capacity units, following statement should be valid,

$$\sum_{\forall p_j \in P} Np_{ij} \cdot Xp_j \geq Nw_i \text{, for } \forall e_i \in E$$

where:

Xp_j indicates how many times p_j is selected as a part of solution. This can be 0, 1, ..., and

Nw_i indicates number of units of working capacity on a link e_i.

An example of the matrix for a network from Figure 2.28, and set of available p-cycles from Figure 2.29 is illustrated in Table 2.5. Together with number of working capacity units on each link (Nw_i), table also shows following;

Np_j number of units of capacity required by p-cycle p_j

Nwp_j maximum number of units of working capacity a p-cycle p_j can protect, defined as,

$$Nwp_j = \sum_{\forall e_i \in E} Np_{ij}$$

PPE_j, potential protection efficiency for a p-cycle p_j, defined as,

$$PPE_j = \frac{Nwp_j}{Np_j}$$

From the table it is clear that:

- $Xp_1 \geq 2$, since $\sum_{\forall p_j \in P \setminus p_1} Np_{(A-B)j} = 0$, $\sum_{\forall p_j \in P \setminus p_1} Np_{(A-C)j} = 0$, $Nw_{(A-B)} = 2$, and $Nw_{(A-C)} = 2$.

This means that of all possible p-cycles only p_1 can protect single unit of working capacity on links A-B and A-C.

Table 2.5. – An example of $E \times P$ matrix

Np	p_1	p_2	p_3	p_4	p_5	p_6	Nw_i	$\mathbf{Np}\cdot\mathbf{Xp}_1$	$\mathbf{Np}\cdot\mathbf{Xp}_2$
A-B	1						2	2	2
A-C	1						2	2	2
B-C	2		1			1	4	4+1	4+2
B-D	1		2	1		2	2	2+2+2	2+4
C-D	1		1		1	1	2	1+1+1	2+2
B-E			1	1		1	3	2+1+1	2+2
D-E		1	1	2	1	2	3	4+1+2	4+4
E-G		1		1	1	1	4	2+1+1	2+2
D-G		2		2	2	2	2	4+2+2	4+4
D-F		1		1	2	1	1	2+2+1	2+4
F-G		1		1	1	1	3	2+1+1	2+4
C-F					1	2	3	1+2	4
Np_j	4	4	4	5	5	6	31		
Nwp_j	6	6	6	9	9	14			
PPE_j	1.5	1.5	1.5	1.8	1.8	2.3			
$\mathbf{Xp}_1$	2			2	1	1		8+10+5+6	
$\mathbf{Xp}_2$	2			2		2			8+10+12

It is clear now that after the set of available p-cycles **P** is determined, an optimization variable is a vector **Xp**. The table shows two possible solutions for **Xp**: $\mathbf{Xp}_1$ and $\mathbf{Xp}_2$. Total number of spare units can be calculated as follows,

$$Np(\mathbf{Xp}) = \sum_{\forall p_j \in \mathbf{Xp}} Xp_j \cdot Np_j \,,$$

and for presented solutions this amounts to,

$$Np(\mathbf{Xp}_1) = 8 + 10 + 5 + 6 = 29 \,,$$

$$Np(\mathbf{Xp}_2) = 8 + 10 + 12 = 30 \,.$$

The efficiency of a solution in terms of capacity redundancy could be calculated as follows,

$$Ef(\mathbf{Xp}) = \frac{Nw}{Np(\mathbf{Xp})} = \frac{\sum_{\forall e_1 \in E} Nw_i}{Np(\mathbf{Xp})} \,.$$

We can end our discussion with following conclusions concerning optimal design:

- Chose p-cycles with lower number of spans and higher number of straddling spans. This optimization could be injected into procedure for enumerating p-cycles. This is also important in regards to total length an optical signal will travel on its way from the source node to destination node, and corresponding degradation in optical fiber, amplifiers and other active optical components.
- When choosing p-cycles consecutively, one after each other, design procedure should also take into account the actual protection coverage of p-cycle.

Actual protection coverage of p-cycle is defined as number of units of working units that are actually protected by the considered p-cycle. For example, consider a p-cycle p_6 from the previously explained example. The p-cycle requires $Np_6 = 6$ units of capacity to be used, and it can potentially protect $Nwp_6 = 14$ units of working capacity on set of links {(*B*-*C*), (*B*-*D*), (*C*-*D*), (*B*-*E*), (*D*-*E*), (*E*-*G*), (*D*-*G*), (*D*-*F*), (*F*-*G*), (*C*-*F*)}. Thus, we can say that its potential protection coverage is 14, or Nwp_6. Furthermore its potential protection efficiency is,

$$PPE_j = \frac{14}{6} = 2.3\,.$$

On the other hand, as previously said, if there are no unprotected units of working capacity on a set of links that p-cycle can protect, actual protection coverage marked $N'wp_j$ will be lower than Nwp_j. Clearly,

$$N'wp_j \le Nwp_j \text{ for } \forall p_j \in P\,.$$

We can also define actual protection efficiency as,

$$PPE'_j = \frac{N'wp_j}{Np_j}\,.$$

2.6.3.3. Enumeration of Cycles

It can be shown that in the worst case number of elementary cycles in a network grows proportionally to factorial function of number of nodes in a network |**E**| (|**E**|!). For example, for a complete directed graph (CDG) (worst case) it can be shown that the number of elementary cycles equals to,

$$N_{EC\_CDG} = \sum_{i=1}^{|\mathbf{E}|-1} \binom{|\mathbf{E}|}{|\mathbf{E}|-i+1} \cdot (|\mathbf{E}|-i)!\,.$$

In case of a complete uni-directed graph (CUG), number of elementary cycles is half the value in CDG,

$$N_{EC\_CDG} = \frac{1}{2}\sum_{i=1}^{|\mathbf{E}|-1} \binom{|\mathbf{E}|}{|\mathbf{E}|-i+1} \cdot (|\mathbf{E}|-i)!\,.$$

Some of the values are illustrated in Table 2.6.

Table 2.6. – Number of elementary cycles in CDG and CUG

|**V**|	3	4	5	9	11	21	50
N_{EC_CUG}	1	7	37	62 814	5 488 059	3.48120×10^{18}	8.43972×10^{62}
N_{EC_CDG}	5	20	84	125 664	10 976 173	6.96241×10^{18}	16.87940×10^{62}
$n!$	6	24	120	362 880	39 916 800	51.09090×10^{18}	304.14100×10^{62}

Obviously, enumerating all of the elementary cycles is impossible even for a network of practical size due to memory constraints. For example, consider a network with 11 nodes, and assume that 20 bytes on average are required to store single cycle. It would require more than 200 Mbytes to store all cycles. Another problem would be to traverse such huge list. Thus, some limits should be defined for possible cycle candidates, in terms of cycle length, circumference, or some other criterions.

2.6.3.4. Additional Issues

Original p-Cycle concept does not provide protection capability in case of node failure. In [PC07] and [PC04] additional concept of node encircling p-cycles was introduced. In this thesis we do not assume application of this concept.

A distributed algorithm for self organization of p-cycles is presented in [PC01], and also discussed in [PC04]. The protocol is termed “Distributed Cycle PreConfiguration (DCPC)”.

In [PC04] the application of the concept of p-cycles to the IP layer has been presented.

In [PC05] a comparison of important conceptual and technical differences with enhanced rings [RR01] and oriented cycle double covers [RR02] is given. The concept of enhanced rings and oriented cycle covers has been discussed in previous sections.

Finally, regarding node structure, [PC04] shows potential ADM-like nodal device for p-cycle networks.

2.7. Network Management and Control

Currently, optical transport networks mostly use manual lightpath provisioning. This is possible due to the fact that changes in traffic requirements can be measured in terms of months, or days at best. However, somewhat similar case was with the telephone network more than a century ago. With the growth of traffic demands, and development of optical devices, one can envision evolution of current optical transport networks into intelligent optical networks (ION) capable of providing automatic lightpath provisioning in a way similar to telephone network.

In ION, network management and control functions are provided by control plane. There are three main functions that control plane provides;

- Resource discovery – provides a mechanism to keep track of the network resource availability, such as traffic ports, bandwidth and multiplexing capability. One of the important aspects of the functionality is network elements addressing.
- Routing control – Provides the routing capability, topology discovery and traffic engineering.
- Connection management – Utilizes the above functions to provide end-to-end service provisioning for different services. It includes connection creation, deletion, modification, and query.

In addition to the basic functions, the control plane also provides protection and restoration capabilities (P&R).

Introduction of distributed control plane should result in Automatic Switched Optical Network (ASON), for which architectural framework has been developed by ITU [CM01][CM03]. In ASON, lightpath provisioning process is automatic. Requests for lightpath provisioning are sent by user (i.e. client network operators) through User-Network Interface [CM05]. There are two major candidates for ASON control plane, Generalized Multi-Protocol Label Switching (GMPLS) and O-PNNI [CM06]. In [GN01], a brief comparison between PNNI based ASON control plane and GMPLS based control plane is given. In short, O-PNNI is an adaptation of ATM PNNI, developed to be an alternative control plane to the one provided by GMPLS. GMPLS [CM02][CM04] is under process of standardization by Internet Engineering Task Force (IETF).

2.7.1. GMPLS Architecture

In GMPLS architecture, similar to MPLS [CM07], generic network element is label switched router (LSR) which makes routing (or switching) decision based on the interface and label. Generally, a label is attributed to an incoming signal in a certain way. For example, in the MPLS, a label is a simple number inserted at the beginning of a packet or cell.

GMPLS extends the original MPLS architecture, so that it includes LSRs that do not recognize packet or cell boundaries. Such LSRs include devices where the switching decision is based on time slots, wavelengths, or physical ports.

GMPLS divides interfaces on LSRs into the following classes:

- Packet Switch Capable (PSC) interfaces. Examples are interfaces on IP and MPLS routers.
- Layer-2 Switch Capable (L2SC) interfaces. Examples are interfaces on Ethernet bridges, and interfaces on ATM-LSRs.
- Time-Division Multiplex Capable (TDM) interfaces. Examples are interfaces of a SONET/SDH Cross-Connect (XC), Terminal Multiplexer (TM), or Add-Drop Multiplexer (ADM), interfaces providing G.709 TDM capabilities (the "digital wrapper") and PDH interfaces.
- Lambda Switch Capable (LSC) interfaces. Interfaces that switch data based on the wavelength on which the data is received.
- Fiber-Switch Capable (FSC) interfaces. Interfaces that switch data based on a position of the data in the (real world) physical spaces.

A hierarchy of the interfaces is shown in Figure 2.32. Note that PSC interface can be interchanged with L2SC interface which deals with cells (ATM) or frames (Ethernet).

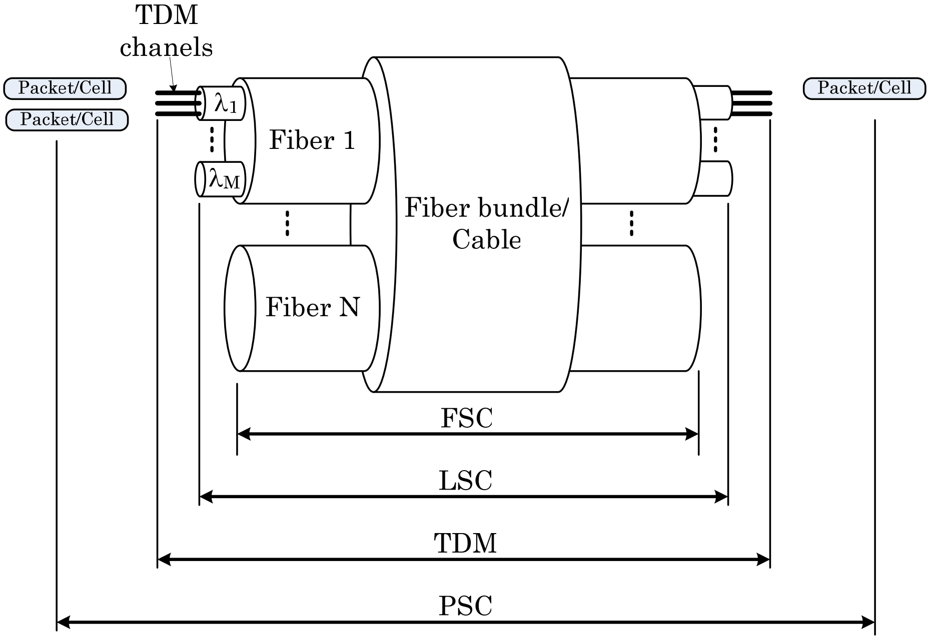


Figure 2.32. – An illustration of GMPLS types of interfaces

A circuit or connection can be established only between, or through, interfaces of the same type. In the context of GMPLS, all these circuits are referenced by a common name: Label Switched Path (LSP). For example, a lightpath is an LSP between two LSC interfaces. In the same way a wavelength channel is also a LSP between two LSC interfaces.

The concept of nested LSP (LSP within LSP), facilitates building a hierarchy of LSPs (forwarding hierarchy). This hierarchy of LSPs can occur on the same interface type, or between different interface types.

For example, a hierarchy can be built if an interface is capable of multiplexing several LSPs from the same technology (layer), e.g. a lower order SONET/SDH LSP (e.g. VT2/VC-12) nested in a higher order SONET/SDH LSP (e.g. STS-3c/VC-4). Several levels of signal (LSP) nesting are defined in the SONET/SDH multiplexing hierarchy.

The nesting can also occur between different interface types (Figure 2.32). At the top of the hierarchy are FSC interfaces, followed by LSC interfaces, followed by TDM interfaces, followed by L2SC, and followed by PSC interfaces. This way, an LSP that starts and ends on a PSC interface can be nested (together with other LSPs) into an LSP that starts and ends on a L2SC interface. This LSP, in turn, can be nested (together with other LSPs) into an LSP that starts and ends on a TDM interface. In turn, this LSP can be nested (together with other LSPs) into an LSP that starts and ends on a LSC interface, which in turn can be nested (together with other LSPs) into an LSP that starts and ends on a FSC interface.

2.7.1.1. Control Plane Services

GMPLS provides following control plane services:

- End-to-end connection provisioning.
- Bandwidth on demand (BoD).
- Automated traffic engineering.
- Additional protection & restoration.
- Optical Virtual Private Network (O-VPN).

End-to-end connection provisioning is used by network operators in order to establish end-to-end connection between ingress and egress LSRs. Connection parameters are sent to ingress LSR. Routing and signaling protocols will be used to actually establish connection. BoD allows clients to establish the connection in real time. Even more, it also allows the client devices to request additional bandwidth in real time, as needed.

2.7.1.2. Control Plane Protocols

Control plane protocols are used to achieve function and services of the control plane. In the context of GMPLS these protocols can be divided into following classes:

- Signaling protocols.
- Routing and traffic engineering protocols.
- Resource discovery protocols.

GMPLS is only one of the key protocols in a control plane protocol set. Signaling protocol is another key protocol. The signaling protocol is responsible for all the connection management actions; set up of a LSP, removal of a LSP, modification of LSP, and retrieval of information about LSP. Currently, there are two different signaling protocols that can be used in connection with GMPLS, Constraint-based Routing-Label Distribution Protocol (CR-LDP) [CM08] and the Resource reSerVation Protocol – Traffic Engineering Extension (RSVP-TE) [CM09]. The major enhancements for GMPLS are:

1. Label exchange to include non-packet networks (generalized labels).
2. Establishment of bidirectional LSPs.
3. Signaling for the establishment of a back-up path (protection Information).
4. Expediting label assignment via suggested label.
5. Waveband switching support—set of contiguous wavelengths switched together.

Routing protocols are used for the auto-discovery of network topology, and to advertise resource availability (e.g., bandwidth or protection type). There are two routing protocols, extended to support traffic engineering functions that are used with GMPLS. They are Intermediate System-Intermediate System with traffic engineering extensions (IS-IS TE) [CM11][CM12], and Open Shortest Path First with traffic engineering extensions (OSPF TE) [CM13][CM14] The major extensions for GMPLS are:

1. Advertising of link-protection type (1+1, 1:1, unprotected, extra traffic).
2. Implementing derived links (forwarding adjacency) for improved scalability.
3. Accepting and advertising links with no IP address—link ID.
4. Incoming and outgoing interface ID.
5. Route discovery for back-up that is different from the primary path (shared-risk link group).

Link management protocol (LMP) [CM10] is used for a resource discovery functions. LMP is used between two adjacent systems (LSRs) for link provisioning and fault isolation. LMP can be used for any type of LSRs, however, it is particularly useful in photonic switches. Main functions of LMP are:

1. Control-Channel Management: Established by negotiating link parameters (e.g., frequency in sending keep-alive messages) and ensuring the health of a link (hello protocol).
2. Link-Connectivity Verification: Ensures the physical connectivity of the link between the neighboring nodes using a PING–like test message.
3. Link-Property Correlation: Identification of the link properties of the adjacent nodes (e.g., protection mechanism).
4. Fault Isolation: Isolates a single or multiple faults in the optical domain.

Figure 2.33 shows GMPLS protocol stack diagram. Note that the IS–IS TE routing protocol stack is similar to OSPF–TE protocol stack with the exception that, instead of IP, connectionless network protocol (CLNP) is used to carry IS–IS TE's information.

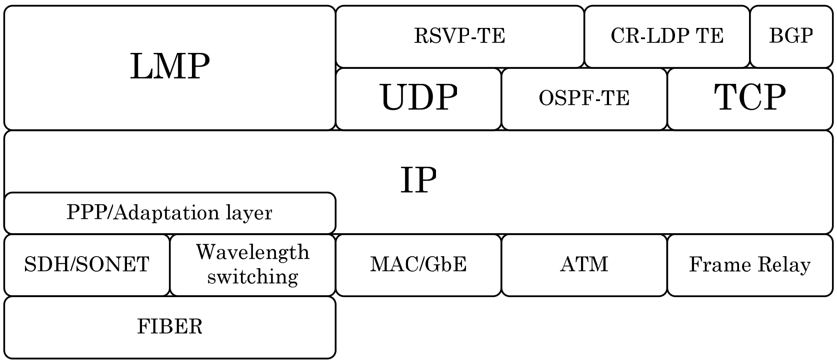


Figure 2.33. – GMPLS protocol stack diagram

2.7.1.3. Link Bundling

Link bundling allows grouping of several links into single logical link, and its advertisement into the routing protocol. Advantages of such method are;

- Reduction of link-state database
- Reduction in number of links that needs to be advertised.
- Only single control channel (for LMP) is required.

- Reduced number of control messages in signaling and routing protocols,

However, there are restrictions in bundling links. Links in a bundled link must:

- Begin and end on the same pair of LSRs.
- Be of the same link type (e.g., PTP or multicast).
- Have the same traffic metric (e.g., protection type or bandwidth).
- Have the same switching capability: PSC, TDMC, LSC, or FSC.

Disadvantage of bundled links is that they result in loss of granularity in the network resources.

2.7.1.4. Reliability

Here we discuss reliability issues in GMPLS, which are described in more detail in [CM15][CM16][CM17].

Fault-management process in GMPLS is composed of the following steps:

1. Detection, handled at the layer closest to the fault. This could be for example at the FSC interfaces indicated as a loss of light (LOL).
2. Localization, the goal is to determine the location of the failure. This is accomplished by a LMP handshake between two adjacent nodes.
3. Notification, LMP is used to notify nodes responsible for restoration, and RSVP TE Notify message for failures between non neighboring nodes.
4. Resolution, switchover of failed path to a pre-allocated LSP, which is a fast switchover (protection), or dynamically create new LSP (restoration).

GMPLS provides both protection and restoration mechanisms, either between end-to-end nodes (on path level), or between two adjacent nodes (link or span level). Thus, there are four P&R mechanisms:

- span protection
- path protection
- span restoration
- path restoration

The OSPF and IS–IS extensions for GMPLS advertise the link-protection-type parameter to include span protection while the route is being computed. After the route is computed, signaling to establish the backup paths is carried out via RSVP–TE or CR–LDP. For span protection, 1+1 or M:N protection schemes are provided by establishing secondary paths through the network and using signaling messages to switch from the failed primary path to the secondary path. Figure 2.34 depicts span and path protections.

In case of a path (end-to-end) path protection, the primary and secondary paths are computed and signaled to indicate that the two paths share reservations. Shared-risk link group is an optional mechanism that allows the establishing of back-up LSPs that do not have any links in common with the primary LSP. This is achieved in the routing extension of OSPF/IS–IS.

The restoration of a failed path refers to the dynamic establishment of a back-up path. This process requires the dynamic allocation of resources and route calculation. Two different restoration methods are given: line and path. Line restoration finds an alternate route at an intermediate node. Path restoration is initiated at the source node to route around a failed path anywhere within the path for the specific LSP. In Figure 2.34, node 1 can initiate this new path. In general, restoration schemes take longer to switch to the back-up path, but they are more efficient in bandwidth usage, as they do not pre-allocate any resource for an LSP.

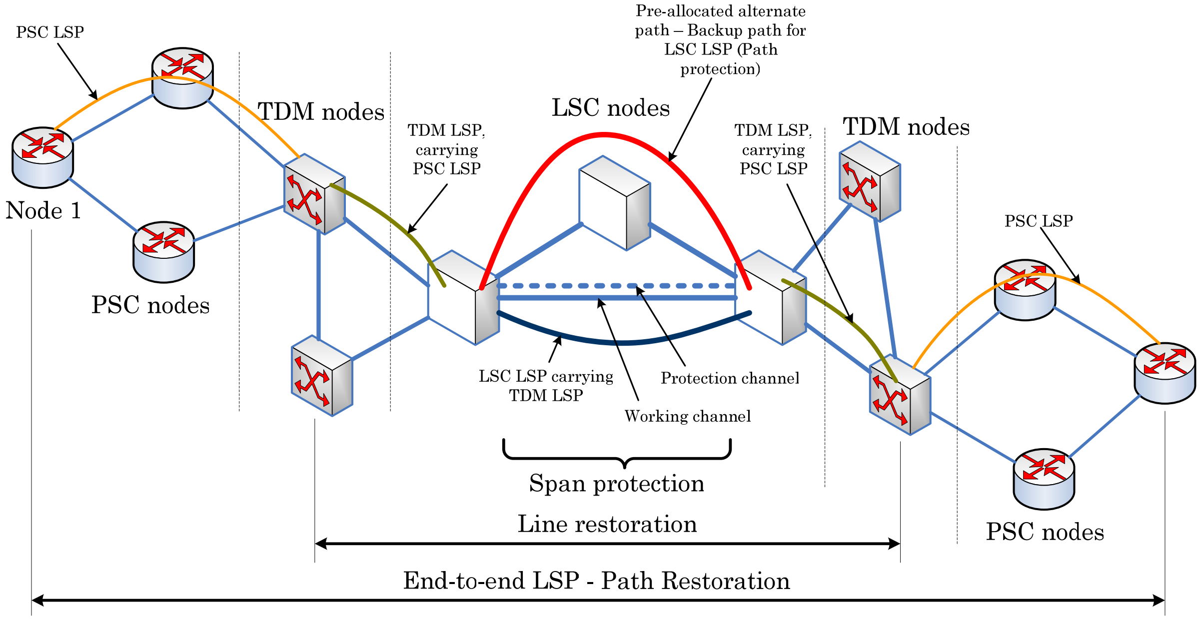
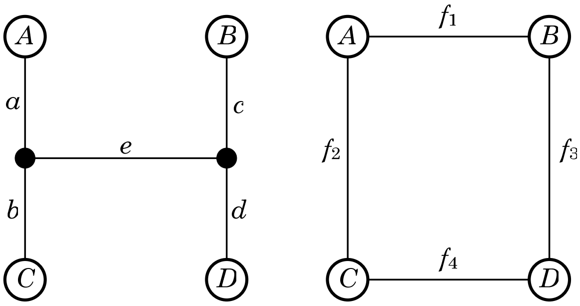


Figure 2.34. – Protection schemes supported in GMPLS

2.7.1.5. Concept of Shared Risk Link Group

Finding diverse protection paths at the optical layer is a special challenge. For example, a lightpath traverses optical cross-connects (OXCs) that are connected by optical fibers. Fibers are placed into conduits, which are buried along a right of way (ROW). For economic reasons, service providers rent ROWs from third parties, such as the railroad companies. As a result, two diverse fiber links at the OXC layer may be placed into the same conduit at the conduit layer and are subject to a single point of failure. Such links cannot be regarded as diverse links when being used to compute working and protection path pairs. Shared risk link group (SRLG) was proposed to address this problem [CM18].

An SRLG is a group of links that are subject to a common risk, such as a conduit cut. Therefore, finding a pair of diverse paths in the optical layer involves finding a pair of SRLG-diverse paths. Each link at the OXC layer may be related to several SRLGs. Although the concept of SRLG was originally proposed to deal with conduit cuts, it can be extended to include general risks. For example, all the fiber links located in a geographic area may be assigned the same SRLG considering the risk of earthquakes.



Fiber segment topology

Fiber link topology

Figure 2.35. – An example topologies for an illustration of SRLGs

Consider a fiber segment topology and fiber link topology as depicted in Figure 2.35. For example, fiber segments could represent optical cables, while fiber links could represent fibers. In the figure A, B, C and D represent locations interconnected by fibers f_1, f_2, f_3, and f_4, and a, b, c and d are fiber segments, or cables.

In the topology, obvious SRLGs are:

- a – the cut of a will also break f_1 and f_2
- b – the cut of a will also break f_2 and f_4
- c – the cut of a will also break f_1 and f_3
- d – the cut of a will also break f_3 and f_4
- e – the cut of a will also break f_1 and f_4

We can represent relationships between risks (resources, lower layer links), which are in this case optical cables, and optical links (higher layer links), in this case optical fibers, by the shared risk relationships (SRR) graph. In the SRR graph, higher layer links (fibers) are represented as nodes. Nodes in a SRR graph (higher layer links) are interconnected if they share common risk. For the example fiber segment and fiber topologies, SRR graph is shown in Figure 2.36.

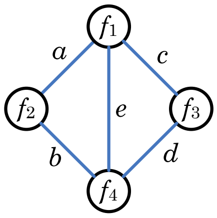


Figure 2.36. – Example of Shared Risk Relationship (SRR) Graph

These 5 SRLGs can be replaced by two SRLGs, S_1 and S_2, which constitute minimum edge covering with cliques (A clique of a graph G is a sub-graph of a graph G in which any two nodes are directly connected). S_1 and S_2 are,

$$\begin{aligned} S_1 &= \{f_1, f_2, f_4\} \\ S_2 &= \{f_1, f_3, f_4\}. \end{aligned}$$

It becomes clear that two paths have to be SRLG independent, i.e. not in the same SRLG, in order to provide network survivability in case of a single failure. For example, optical fiber f_2 and f_3 are SRLG independent.

In a GMPLS, SRLG is defined as set of GMPLS managed links that share common resource, and thus common risk. The set of links belongs to the same SRLG, if they are established over fiber links passing through the same fiber sub-segments sequence (for example, fiber trunk) and through the same fiber segment between two OXCs. An LSP covers a SRLG only if it crosses one of the links within SRLG.

The concept of SRLGs has been extended to include nodes, and thus we have Shared Risk Node Groups, (SRNG). Finally, the whole concept has been generalized into Shared Risk Resource Group (SRRG) in [CM19].

3.

Multi-Service Photonic Network

The chapter deals with the architecture of what we term Multi-Service Photonic Network (MSPN). In the first part, architecture of MSPN is presented. The part starts with the background and motivation. Then, a layered perspective of the MSPN architecture is given. Functions and transport entities for each layer are explained. Next, control services and functions are discussed. In this context a relation with GMPLS is explained.

The second part of the chapter explains generic node structure. Functional description of the switching elements and transport interfaces is presented. This is followed by the discussion on the possible ways of transporting optical packet/burst switching services over optical circuit switching services. Finally, we also discuss on ways in which different topological and P&R paradigms can be mapped onto MSPN.

In the last part of the chapter, a view of evolution towards MSPN is presented. We start with an overview of the current situation in optical networks. Next, current status of switching paradigms is presented. Then we discuss about the situation where a single operator has different switching paradigms in the network, and the ways of the distribution of transmission network resources to switching paradigms. We also discuss hybrid networks, and their relation to MSPN. In hybrid networks a node can support only a subset of switching paradigms.

In the final part of the chapter we discuss advantages and disadvantages of proposed MSPN architecture.

3.1. Architecture of Multi-Service Photonic Network

3.1.1. Background

The main idea of the MSPN is to provide three classes of services to its users or client networks. These services are;

- Optical circuit switching, through the OCS layer,
- Optical burst switching, through the OBS layer, and

- Optical packet switching, through the OPS layer.

This is very similar to current transport network architectures, in which network operators provide basically two major service classes. The first is traditional circuit switched service, through different PDH/SDH/SONET interfaces, and in some cases through ATM interfaces. For example, the service is used for voice transfer or any other service with stringent requirements on time relations, e.g. delay and delay variation. An attempt has been made by some network operators to offer circuit switched services through the ATM, but since ATM was always transferred over SDH/SONET in long haul networks, many network operators dropped the idea. In addition to the requested bandwidth, additional parameters concerning resilience to failures can be specified for the service.

The second major class of service offered by today's networks is packet switched service. Examples are: IP, which is nowadays predominant packet switched service, Frame Relay, and X.25. The packet switched service is defined by a number of traffic and quality of service (QoS) parameters. Their values, in terms of expected mean values or limits, are defined within service level agreement (SLA).

The constant growth of telecommunication traffic demands forces network operators to flatten their network protocol stacks (for example, to remove ATM) in order to cope with traffic demands more efficiently. By removing ATM, which is one of the mature technologies supporting QoS, intelligence that was once in the ATM layer has to be moved either to the upper layers, most probably IP, or to the lower layers, obviously optics. One solution is to move some parts of the network intelligence to the optical layer, and other parts to the IP layer.

It is expected that in the near future signal processing in the optical domain will not be flexible and efficient as it is in the electrical domain. The consequence is that the introduction of network intelligence, previously available in the "copper" layers, to the optical layer will be limited.

The MSPN is based on the previous premise. We expect to see gradual shift of packet switching paradigm from the "copper" layer to the optical layer. MSPN architecture is defined so that it will allow incorporation of different switching paradigms as they evolve and mature. For example, one can expect that the first step in this direction will be the usage of optical burst switching, as an intermediate step on the way to introduce optical packet switching. MSPN is architecured in a way so that it allows coexistence of optical packet and burst switching, and other switching paradigms as well, as they might appear.

In addition to different switching paradigms, MSPN architecture allows mapping of different topological paradigms and their respective P&R schemes onto physical network topology.

Figure 3.1 depicts topological view of a MSPN. The traffic from the various sources (e.g. voice, data) is aggregated at edge switches. Note that edge nodes are not part of the MSPN. An operation, called *traffic grooming* [TG01], imposed on the low order traffic streams, employs multiplexing at the input and de-multiplexing at the output of the network, and optional switching in the intermediate nodes.

Note that input to an edge switch can be both electrical and optical, but connection to the core network, MSPN, is through optical fiber medium (possibly in baseband mode) at speed rates that cannot be processed electronically. Note that depicted topological view of the MSPN does not imply type of switching paradigm that will be used.

Structure of all-optical nodes depends mostly on the switching scheme, the most complex switching scheme being that of the optical packet switching. As previously stated, similar to the "copper" networks, one can imagine architectural shift from the copper to the fiber. In this regard, the future all-optical network would support at least two, or even more switching paradigms simultaneously. If the network implements OPS, or OBS, then it is easy to implement circuit switching through the control plane.

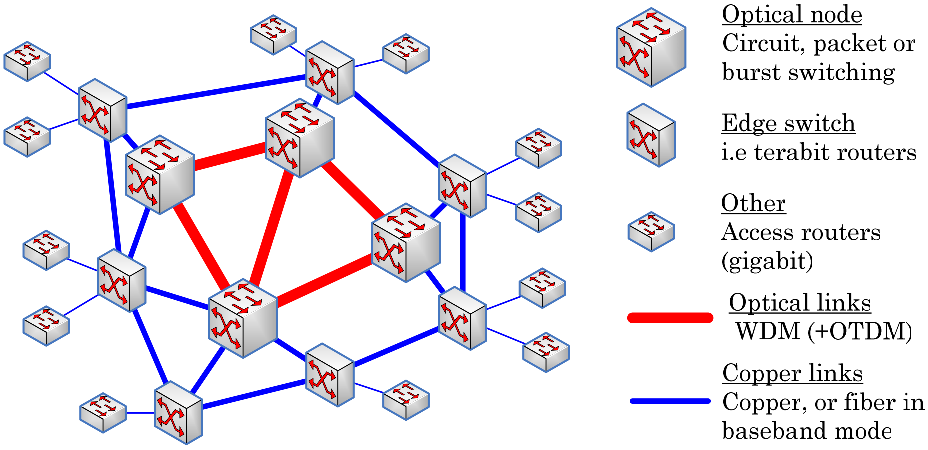


Figure 3.1. – An example of MSPN topology

Such network is supposed to combine efficiency of packet (or burst) switching with the quality and predictability of delay and delay variation present in the circuit switched optical networks. For example, if a user wants service of data transfer (i.e. aggregation of traffic from huge number of Internet home users), the MSPN could decide to serve such request through packet or burst switching resources. On the other hand, network provider or "big users" could ask for constant connection with guaranteed capacity, delay, and most importantly, delay variation (voice, video). In this case, all-optical network could serve request through circuit switching.

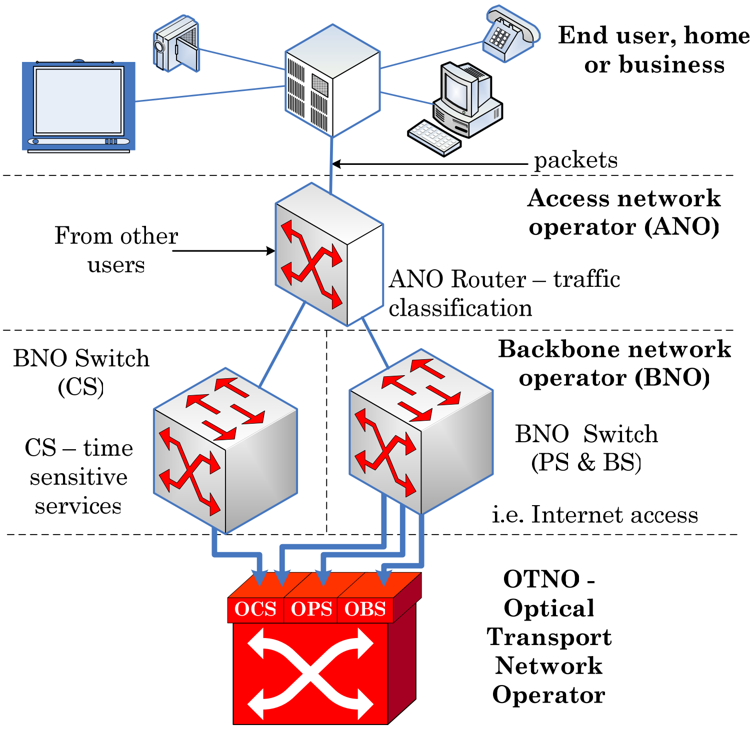


Figure 3.2. – An example of MSPN users

Figure 3.2 shows an example on what kind of users an MSPN operator might have. In the context of the figure MSPN operator is termed Optical Transport Network Operator (OTNO).

The figure shows three levels of network operators. An access network operator (ANO) deals directly with end users, home or business. At this level, due to the fact that traffic volumes from its clients are low, an ANO might provide packet switched interface to its users. Traffic and QoS parameters can be controlled at this level due to the relatively low traffic volumes.

ANO makes traffic classification at his routers (ANO router). Traffic which is time sensitive will be sent to the backbone network operators through circuit switched interface, or possibly through burst switched interface. At this level, in terms of traffic and QoS parameters, traffic volumes are difficult to handle. Note that separate BNOs might be used for packet/burst switched services and for circuit switched services.

Finally, optical transport network operator (OTNO) will offer both circuit and packet switched service to its clients, which are BNOs. A BNOs will, depending on its business decisions, in a way similar to ANOs, make decisions on ways how to route different traffic types. For example, a BNO may route some of its clients traffic through burst switched service instead of packet switched, or even through circuit switched service.

The goal of all service providers, e.g. network operators, is to fulfill SLAs made with their respective clients in a way that will result in higher profits.

3.1.2. MSPN Layers

The section gives a brief description of the MSPN architecture. We start with a layered perspective. Figure 3.3 shows layered view of the MSPN architecture. The layers are, from the bottom to the top:

- Optical Transmission section (OTS),
- Optical Multiplex Section (OMS),
- Optical Channel Section (OCh),
- Optical Switching Services layer (OSS).

OSS layer is divided into following parallel sub-layers:

- Optical Circuit Switching Sub-layer (OCS),
- Optical Packet Switching Sub-layer (OPS),
- Optical Burst Switching Sub-layer (OBS).

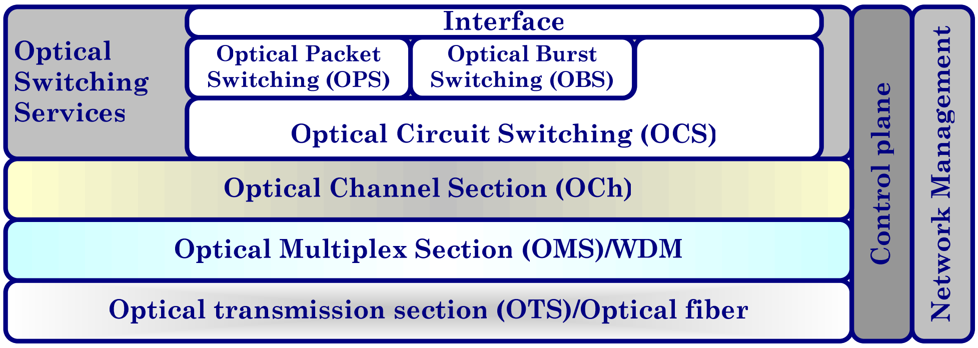


Figure 3.3. – MSPN layers / MSPN protocol stack

The first three layers from the bottom, optical transmission section (OTS), optical multiplex section (OMS) and optical channel section (OCh), are identical to the architecture discussed in [IS01] and [IS02]. The structure and layers in OTN closely parallel the path, line, and section sub-layers within SONET and SDH [SD01]. The function of these layers is identical to that of corresponding layers in OTN architecture [IS02]. Illustration of these layers on a DWDM link in an OTN is shown in Figure 3.4.

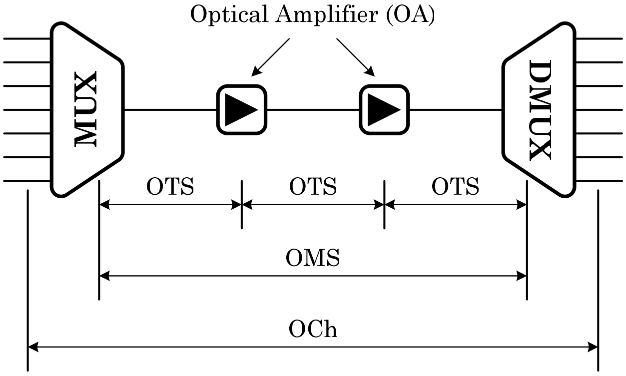


Figure 3.4. – Illustration of OTN layers on a DWDM link

We now give description of each layer, including transport entities offered by the layer to client (higher) layers. A transport entity is defined as the fundamental unit of abstraction in a transport layer. Since any layer that provides service to higher layers can be viewed as transport layer, precise definition of the notion "transport entity" depends on the layer we are referring to.

3.1.2.1. Optical Transmission Section Layer

An OTS is defined on a fiber connecting either two optical amplifiers (line, booster or pre-), or between amplifier and multiplexer or de-multiplexers (see Figure 3.4). Clearly, OTS comprises all wavelength channels within a fiber, but only between two active components (amplifiers, multiplexers and de-multiplexers). This layer could also be termed fiber layer, or fiber chain, since it physically comprises fibers (or chain of spliced fibers).

OTS layer defines physical characteristics of an optical links, such as connectors, optical fibers, optical line signaling, modulation techniques, dispersion and signal management, pulse shaping and other.

The OTS layer allows service providers to manage and monitor physical sections of optical fiber between network elements such as OADM, amplifiers and optical switches. Attributes such as laser signal power levels, dispersion, and loss of signal can be reported to the network operators to facilitate fault isolation.

3.1.2.2. Optical Multiplex Section Layer

Similar to OTS, OMS also comprises all wavelength channels, but, unlike OTS, between a multiplexer in a source node, and de-multiplexer in a destination node. Physically, OMS comprises of optical amplifiers, and fibers, or fiber sections. In context of a network, optical links are only required to implement OTS and OMS layers. An optical link consists of number of OMS's. The number of OMS on a link is equal to the number of optical fibers between two directly connected nodes.

MSPN supports OMS transport entity, which is actually a fiber.

3.1.2.3. Optical Channel Layer

In the MSPN, OCh functionality, similar to that in [IS02], refers to a point-to-point communication which uses single wavelength channel. Thus, OCh physically comprises of a number of OMSs, and multiplexers and de-multiplexers.

There are two transport entities used at this level. Between two optical nodes, directly connected by an optical link, transport entity used at the OCh layer is termed wavelength channel. A wavelength channel is uniquely identified by the triple (defined by expression (2.5)):

- Optical link ID,
- Optical fiber ID, relative to the optical link,
- Wavelength ID, relative to optical fiber.

The Figure 3.5 illustrates transport entities defined at the OMS and OCh layers and their relation.

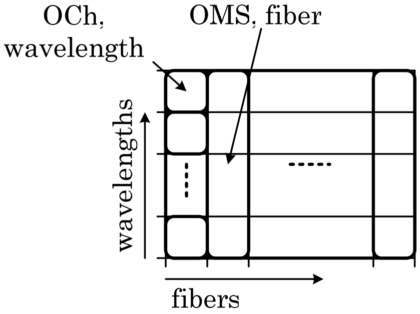


Figure 3.5. – Illustration of transport entities in OMS and OCh layers

Between two end nodes that are not directly connected, transport entity at the OCh layer is termed wavelength path, or lightpath. A lightpath is an ordered sequence of wavelength channels on an optical links that make path between the end nodes. A lightpath is defined by expression (2.20).

3.1.2.4. Optical Circuit Switching Layer

Optical Circuit Switching layer implements the functionality needed to provision lightpaths and other circuit switched transport entities. The layers uses interface to OCh layer in order to route circuit switched traffic demands in the network. Basically, the functionality of OCS layer is similar to that of ASON [CM01].

The transport entities offered by this layer to the upper ones are;

- Wavelength channel (λ),
- Wavelength channel group (λG),
- Lightpath, or wavelength path (Λ),
- Lightcycle, or wavelength cycle (Θ),
- Logical channel, or channel (LCh), and
- Logical connection or connection (LC).

Note that these transport entities also define sub-layers within the OCS layer. Figure 3.6 illustrates OCS transport entities.

A wavelength channel (λ) is a unidirectional point-to-point transport entity, positioned between two directly connected nodes. Wavelength channel addresses lowest unit of circuit switched capacity on an optical link. OCS layer simply provides "pass through" service to the OCh layer in case of this transport entity. A wavelength channel is defined by expression (2.5).

A wavelength channel group (λG) is a unidirectional point-to-point transport entity, positioned between two directly nodes and contains group of wavelength channels (λ). The concept of the wavelength channel group is introduced so as to support the concept of waveband switching (WBS) [WS01] in the MSPN.

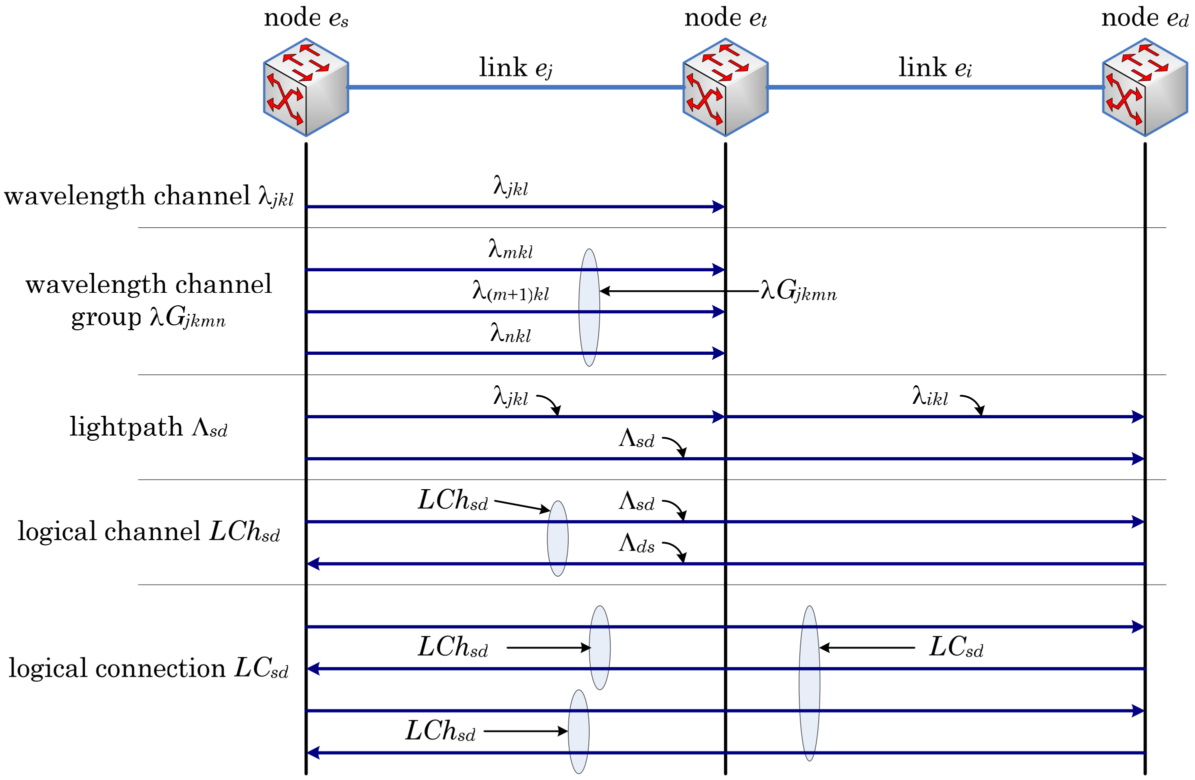


Figure 3.6. – OCS transport entities

A lightpath, or wavelength path (Λ), is a unidirectional transport entity defined on an end-to-end level. Lightpath addresses lowest unit of circuit switched capacity between two end nodes. It comprises ordered sequence of wavelength channels, as defined by expressions (2.20) and (2.25). Note that lightpath can be composed of a single wavelength channel. In this regard, λ can be viewed as a sub-set of a Λ.

A lightcycle, or wavelength cycle (Θ), is a closed loop made of ordered sequence of wavelength channels. By itself, a lightcycle can not be viewed as a transport entity. However, parts of lightcycle can be used a transport entities in certain cases, such as failures on a working transport entities. The concept of lightcycle can be used within ring based and p-cycle based networks.

A lightpath is a unidirectional end-to-end communication. In practice, communication often includes two lightpaths between pair of nodes, in most cases identical in terms of various transmission performances, such as delay and delay variance. In the thesis such transmission entity is called logical channel (*LCh*), or just channel. In the simplest case, channel is composed of two lightpaths, one per direction. Hence, a channel capacity is equal to that of corresponding lightpaths. For a *LCh* we write,

$$LCh_{sd} = \left(\Lambda_{sd}, \Lambda_{ds}\right).$$

Regarding the choice of paths for two lightpaths, Λ_{sd} and Λ_{ds}, two cases are possible:

- *Symmetrical routing*: Two lightpaths are routed (placed) over identical paths. Two paths are identical in terms of number of elements and elements themselves, the only difference being in reverse order of elements. This is the usual way of routing, also assumed in the thesis.

- *Asymmetrical routing*: Two lightpaths are routed over different paths. The problem with this kind of routing is in the fact that non-identical performances for two directions, for example delay, can cause various problems in transmission of upper layer (client) protocols.

At the *LCh* level, one can provide certain protection and restoration paradigms. Depending on the paradigm, a logical channel will contain one or more backup/protection entities. For example, consider 1+1 protection paradigm. In such paradigm, a protection lightpaths will be allocated to the logical channel. Logical channel will contain in this case 4 lightpaths,

$$LCh_{sd} = \left(\Lambda_{sd_w}, \Lambda_{sd_p}, \Lambda_{ds_w}, \Lambda_{ds_p} \right).$$

The index w stands for working, while index p stands for protection. The expression above is also valid for a 1:1 protection, in which protection lightpaths are activated only in the case of a failure on a network element over which working lightpaths are passing through. We need notion of time (relative) in the expressions defining different P&R paradigms. Mathematical description of P&R mechanisms is discussed in the chapter 4.

A demand between pair of nodes could be quite generally much higher than the full wavelength capacity, and thus capacity of a single channel. In such cases, the traffic is distributed across number of channels. Resulting transport entity is termed in the thesis logical connection, or just connection,

$$LC_{sd} = \left\{ LCh_{sdi} : i \in \left\{ 1, \ldots, \left| LC_{sd} \right| \right\} \right\}.$$

It is possible that more than one connection is required per node pair. However, in the work, only one connection is assumed to be required between node pair, and that connection will carry overall demand between the respective node pair.

There are two options in context of connection channels routing:

- *Grouped*: All channels are routed identically, meaning that for all channels, lightpaths in each direction are placed onto identical paths. This is assumed in the thesis.
- *Individual*: All channels within connection are routed individually, meaning that their corresponding lightpaths, one per direction, are routed over different paths.

Note that definitions presented above allow both symmetrical and asymmetrical routing of lightpaths within channel. In the thesis we always assume grouped routing.

Similar to the logical channel layer, P&R mechanisms can be applied at the *LC* level too. For example, one can define logical connection as being available, if at least one of the contained logical channels is available.

3.1.2.5. Optical Packet Switching Layer

OPS layer provides the functionality of the optical packet switching paradigm. Transport entities defined within the layer are;

- Packet,
- Exchange,
- Connection.

Packet is fundamental transport entity in packet switched networks. It is a self-contained unit of transport, meaning that all the routing information necessary is contained within the packet itself, in its header.

A series of packets transferred over the same path in an optical network is called exchange. We assume that certain traffic and QoS parameters will be constant during the exchange.

Connection is a long term transport entity between end nodes, defined by the service level agreement (SLA). During the time interval in which the connection is active, due to the failures in the network, congestion or other reasons, different paths can be used to route packet between end nodes. Thus, a connection is composed of number of exchanges. For certain exchanges, SLA could be meet, while for others not.

Connection is defined by different traffic and quality of service (QoS) parameters. In the work we do not discuss SLA and QoS issues. These parameters can be for example inherited from the ATM model.

3.1.2.6. Optical Burst Switching Layer

OBS layer provides the functionality of the optical burst switching paradigm. Transport entities are as follows;

- Burst,
- Exchange,
- Connection.

Definitions of transport entities are similar to that of OPS.

3.1.3. Control Plane Services

MSPN will use GMPLS control plane services. Through the GMPLS, MSPN offers following control plane services:

- End-to-end connection provisioning,
- Bandwidth on demand,
- Automated traffic engineering, and
- Optical Virtual Private Network (O-VPN).

In the thesis, control functions of the MSPN are not discussed in detail. The following subsections give a brief overview of some control plane services.

3.1.3.1. End-to-end Connection Provisioning

The service is used by MSPN operator to automatically establish an end-to-end connection. Request will be processed on the network management station. Software will determine best route in defined terms, and through the use of signaling protocols, a solution will be applied to the MSPN. The request specifies type of switching (OCS, OPS or OBS), and additional parameters related to the selected switching type. Request can be rejected through the signaling process in the case the network does not have free resources.

OCS Connections

In the OCS, two main parameters are address of the destination node, and the type of connection;

- Wavelength channel,
- Wavelength channel group,

- Lightpath,
- Lightcycle,
- Logical channel,
- Logical connection

Additional parameters need to be specified through signaling interface. These parameters will be specific for each type of OCS connection. For example, in a wavelength channel group request, a number of wavelengths should be specified. Optionally, suggested or requested wavelengths should be specified.

OPS/OBS Connections

In the OPS/OBS, in the signaling process optional traffic and QoS parameters will be specified together with the address of the destination node. Traffic and QoS parameters will be different for OPS and OBS.

3.1.3.2. Bandwidth on Demand

The bandwidth on demand (BoD) service enables clients of the MSPN automatic provisioning of the end-to-end connection. Through the use of signaling protocols, a request is sent to the MSPN. The request specifies type of switching (OCS, OPS or OBS), and additional parameters related to the selected switching type. Request can be rejected through the signaling process in the case the network does not have free resources. This is an extension of an end-to-end provisioning service.

The BoD service allows dynamic request for additional transport entities, such as lightpaths, by users of the MSPN. For example, the service allows dynamic provisioning of additional logical channels for the logical connection. The capacity carried by the logical connection will be increased by the capacity of added logical channel (usually full wavelength capacity). BoD also allows dynamic releasing of logical channels within logical connection.

In OPS and OBS, this service effectively becomes dynamic change of traffic parameters.

3.1.3.3. Optical Virtual Private Network

The optical virtual private network (O-VPN) service allows user full network resource control of a defined partition of the MSPN network. Although the users have full network resource control of that portion of the network, an O-VPN is just a logical network partition, and the end users still do not have visibility and accessibility of the operator’s network.

The service allows end users provisioning of different transport entities. The end users can create and delete connections within the assigned portion of the MSPN.

3.1.4. Control Plane Protocols

Control plane protocols defined within the GMPLS architecture are used in the MSPN in order to enable control plane services, as described above. An overview of control plane protocols for GMPLS is given in 2.7.1.

3.2. MSPN Generic Node Structure

Figure 3.7 shows generic node structure for the MSPN network.

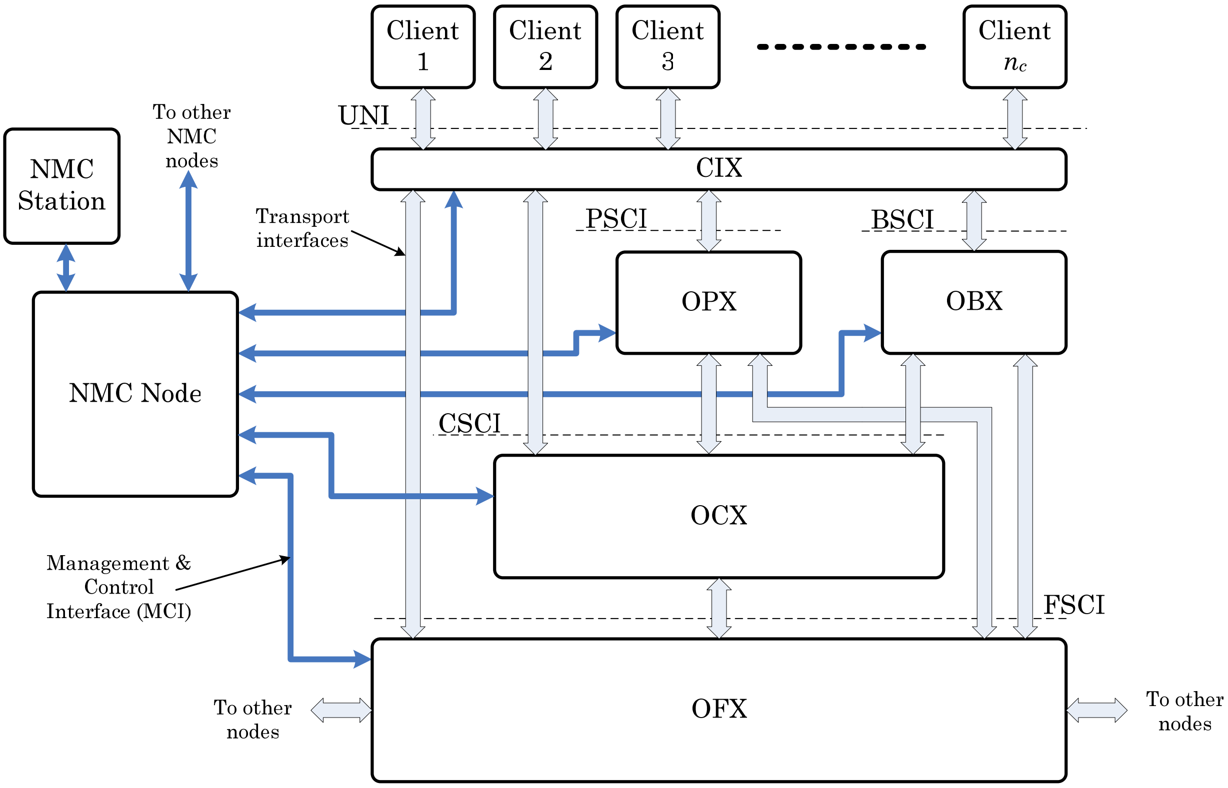


Figure 3.7. – MSPN generic node structure

The components of a MSPN node are divided into following classes;

- Switching elements,
- Transport interfaces, and
- Network management elements and interfaces.

Following switching elements are contained within the node;

- Optical fiber switch (OFX)
- Optical circuit switch (OCX)
- Optical packet switch (OPX),
- Optical burst switch (OBX), and
- Client interface switch (CIX).

The MSPN node defines interfaces between switching elements;

- Fiber switching capable interface (FSCI),
- Circuit/Channel switching capable interface (CSCI),
- Packet switching capable interface (PSCI), and
- Burst switching capable interface (BSCI).

In addition to internal interfaces, listed above, MSPN node handles user requests through User-to-Network Interface (UNI).

Network management and control elements and interfaces are;

- Network management and control (NMC) node,
- Network management and control station, and
- Management and control interfaces (MCI).

3.2.1. Functional Description of the Switching Elements

Optical fiber switch (OFX) is an optical space switch which works at the granularity level of an optical fiber, switching all the wavelengths within the fiber simultaneously. In the first iteration in the evolution of the MSPN, OFX could be manual switchboard in which connections are established manually. Besides providing the capability of offering “dark fiber” service, it also allows the implementation of various P&R schemes on an optical multiplex section level.

Optical circuit switch (OCX) works with the wavelength channels, thus its main function is to switch between different wavelengths within the same or different fibers. It provides the capability of full wavelength conversion. An example of the OCX is shown in Figure 3.8.

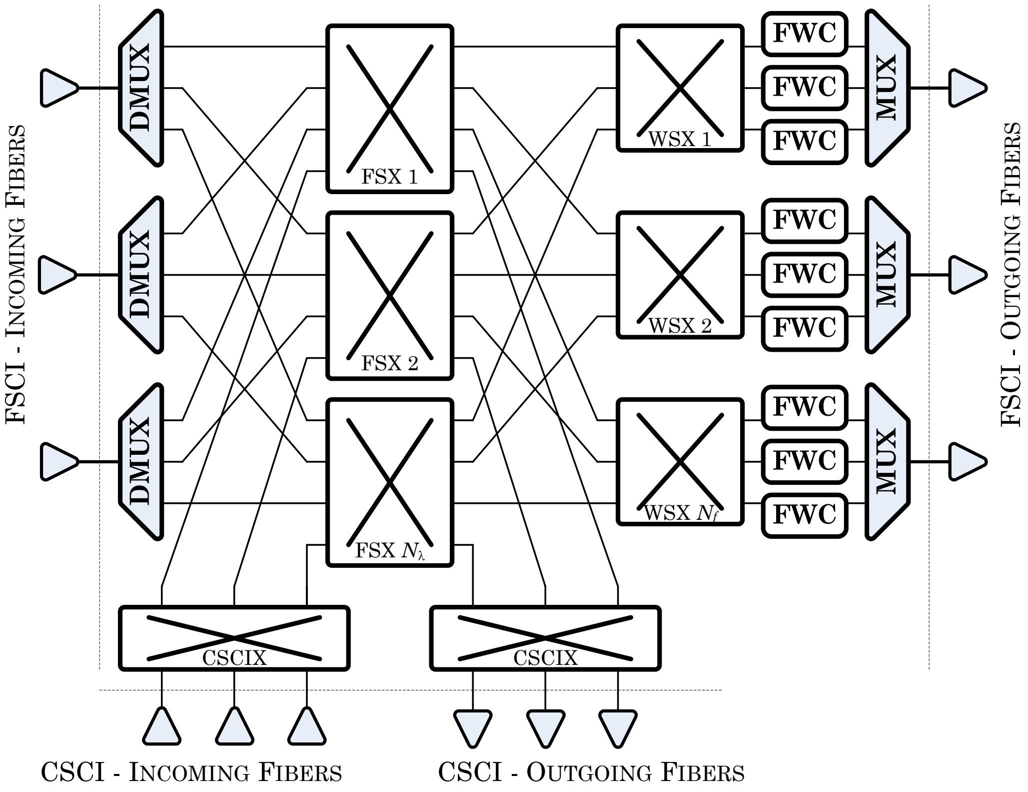


Figure 3.8. – An example of OCX structure

An OCX contains following elements:

- CSCI (Circuit Switch Capable Interface) input space switch (CSCIX),
- Fiber selecting switch (FSX),
- Wavelength selecting switch (WSX),
- Multiplexers (MUX),
- De-multiplexers (DMUX),

- Fixed wavelength converters (FWX),

CSCIX is space switch with the role of selecting first available FSX, or fiber selecting switch. CSCIX should support optical multicasting in order for a MSPN node to support certain P&R paradigms. After the CSCIX, signal is passing over to the FSX. FSX selects requested or available outgoing fiber on the FSCI, and finally, WSX, or wavelength selecting switch selects requested or available outgoing wavelength on an already addressed fiber. In order to adjust the wavelength of an incoming signal to the wavelength of the addressed multiplexer port additional wavelength conversion is required. For that matter, a fixed wavelength converter with any-to-fixed-wavelength conversion capability can be used. De-multiplexers at the incoming part of the FSCI and multiplexers at the outgoing part of the FSCI are used to partition incoming WDM signal into separate wavelength channels, so that additional optical processing can be made at that level.

Optical packet switch (OPX) implements the functionality of the optical packet switching paradigm. We do not discuss the possible structure of the OPX, instead we point out to the overview presented in [PS05]. OPX is assumed to support both CSCI and FSCI interfaces. Clients use services and resources of the OPS network through PSCI.

Optical burst switch (OBX) implements the functionality of the optical burst switching paradigm. We do not discuss the possible structure of the OBX here, but instead we point out to an overview of the architectures and protocols used in OBS presented in [BS09]. Like the OPX, OBX also supports CSCI and FSCI. Clients use services and resources of the OBS network though BSCI.

Support of FSCI and CSCI interfaces by the OPX and OBX allows distribution of the transmission resources to these switching paradigms at levels of fiber and wavelength channel. If requested, OPS or OBS parts of a MSPN can, on selected optical links, control whole fibers, or just portion of them (wavelength channels).

Client interface switch (CIX) is used to connect network users to desired service in terms of switching, topological and P&R paradigm. In general, CIX is an optical space switch, with optional wavelength converters and/or transponders. This will be defined by the User-to-Network Interface (UNI) through which users are connecting to the MSPN. If it will be allowed within UNI for a client to connect to MSPN through a non-ITU WDM grid wavelength, then transponders will be needed. Transponders can be in some cases replaced by wavelength converters. CIX supports UNI, FSCI, CSCI, PSCI and BSCI. If additional switching paradigms will be used in the network, then they need to be supported by CIX.

One of the most important requirements for a CIX is possibility of optical multicasting. The multicasting is required in order to support certain P&R paradigms. It will also allow for an optical multicasting on a network level.

3.2.2. Functional Description of the Transport Interfaces

It is obvious that all interfaces within the MSPN node are physically fibers. Special requirements need to be met for some of them in terms of wavelengths. By this we mean that wavelengths used on MSPN interface should be defined within wavelength grid which is used in MSPN. We call this a MSPN wavelength grid. Note that wavelengths used in all-optical networks are defined by the ITU [IS03], but ITU wavelength grid is defined for different wavelength spacing, while in MSPN only one is expected to be used. Therefore, there is subtle difference between MSPN and ITU wavelength grid.

UNI is expected to support three different classes of interfaces. In the first case, non ITU wavelength grid is used, for example in 2nd (around 1300 nm), or even 1st window (around

850 nm). In this case, clients will be connected to the MSPN through the transponders. In the second case, if an ITU wavelength grid incompatible with MSPN wavelength grid, it will be converted by wavelength converters to a compatible wavelength. Finally, in a third class of interface, clients will be directly connected to the CIX, and through the CIX to the desired type of service. Consequently, UNI does not require strict obedience to the ITU wavelength grid, nor MSPN wavelength grid.

UNI also supports signaling between clients and the MSPN. Through the process of signaling, a user selects appropriate type (or class) of service, and destination user. Signaling information will be used by the network management and control (NMC) node to appropriately configure CIX, and other network resources.

FSCI does not distinguish wavelengths within a fiber. Due to the fact that FSX switch is used, which is an active component, for which transparency over very wide range of wavelengths is very hard to achieve, it will operate on the 3rd optical window, around 1550 nm. The main requirement is to use wavelength range defined for a MSPN wavelength grid.

CSCI, PSCI and BSCI distinguish wavelengths within a fiber. Only wavelengths defined within the MSPN wavelength grid are allowable at these interfaces.

3.3. Encapsulation of OPS/OBS in OCS

In the MSPN, OCS transport entities are used to connect OPX and OBX elements of a MSPN node. Figure 3.9 shows two directly connected MSPN nodes (A and B). Both OBX and OPX support CSCI and FSCI, and they are connected to appropriate switches. In the figure optical packet switches in nodes A and B are connected by two λ/Λ transport entities (wavelength channel/lightpath) and one OMS transport entity (fiber). Optical burst switches are connected by one λ/Λ transport entity and one OMS transport entity.

Possible arrangement of capacity designated to different switching paradigms is also shown. The figure clearly shows that OCX and OFX parts of a MSPN node, in addition to providing circuit switched services at their respective levels of wavelength channel and fiber, are capable of dynamic distribution of optical link capacity among different switching paradigms.

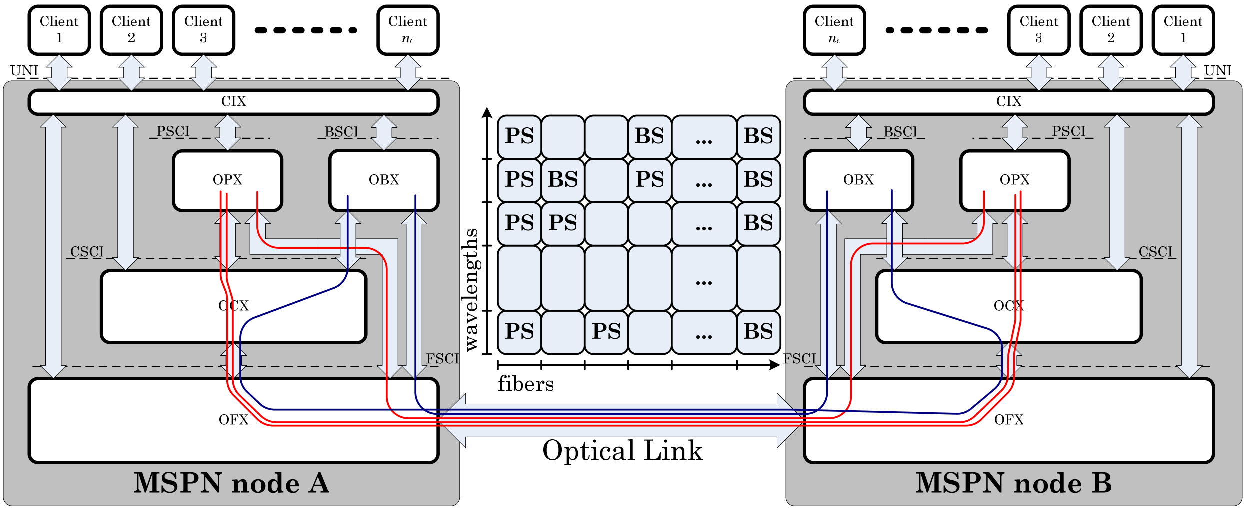


Figure 3.9. – Distribution of optical link resources to different switching paradigms

For example, one of the OCS services is bandwidth on demand (BoD). BoD can be provided not only through the UNI, but also through the FSCI and CSCI. In this regard, OPX, or packet switching part of the MSPN can be viewed as a client of the OCX part of the network. In any case, if OPX node needs additional capacity, it will send request for additional transport services through CSCI or FSCI by the corresponding signaling protocols. This will also work in the opposite direction, for releasing of unneeded capacity.

BoD can be also provided within the OPS and OBS services. This leads to fine-grained division of optical link capacity. An example of link resource distribution among different possible services is show in Figure 3.10.

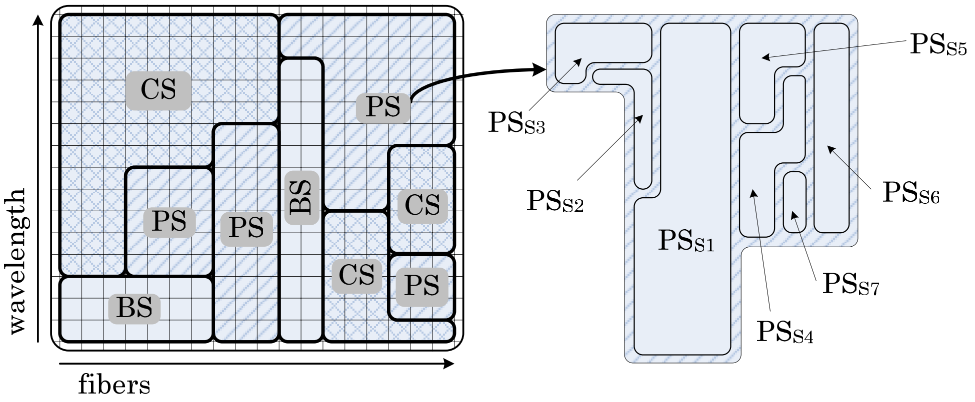


Figure 3.10. – MSPN - Link resource management

There are three possibilities for the encapsulation of OBS/OPS transport entities within OCS transport entities;

1. OPS/OBS use only λ transport entities from the OCS layer (λ case). OBS/OPS layer topology follows OCS topology. OCS provides no P&R, and thus restoration is limited to that of OPS/OBS layers. The advantage of this scenario is that there are no possible negative interactions between P&R schemes implemented at different layers. Disadvantage is in relatively slow restoration time of OPS/OBS in comparison to that of OCS. This scenario is depicted in the Figure 3.11. The figure suggests that single failure at the OCS layer will always result in the single failure at the OPS/OBS layer.

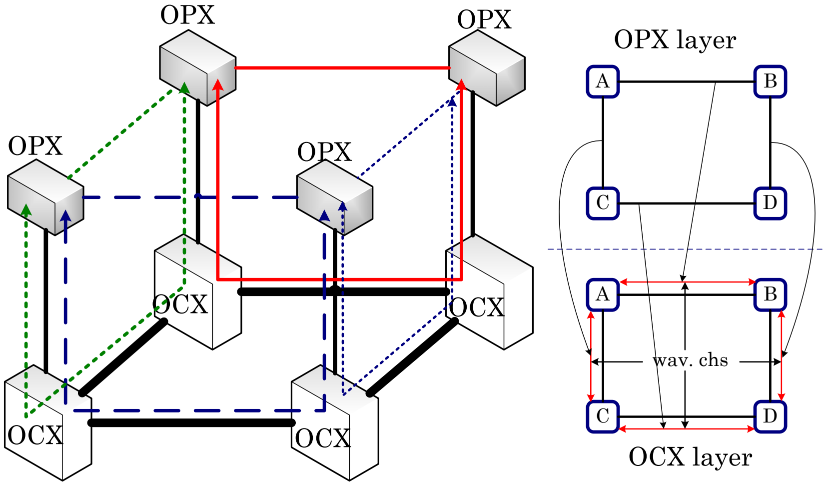


Figure 3.11. – OPS/OBS over OCS: λ case

2. OPS/OBS uses Λ transport entities from the OCS layer (Λ case). OCS layer does not provide P&R, but creates arbitrary OPS/OBS topology over OCS layer. Advantages

and disadvantages are the same as for the previous scenario. Additional advantage is that this scenario allows for a hybrid MSPN network, in which some nodes do not support some of the switching paradigms. The scenario is shown in Figure 3.12. Node B does not support OPS.

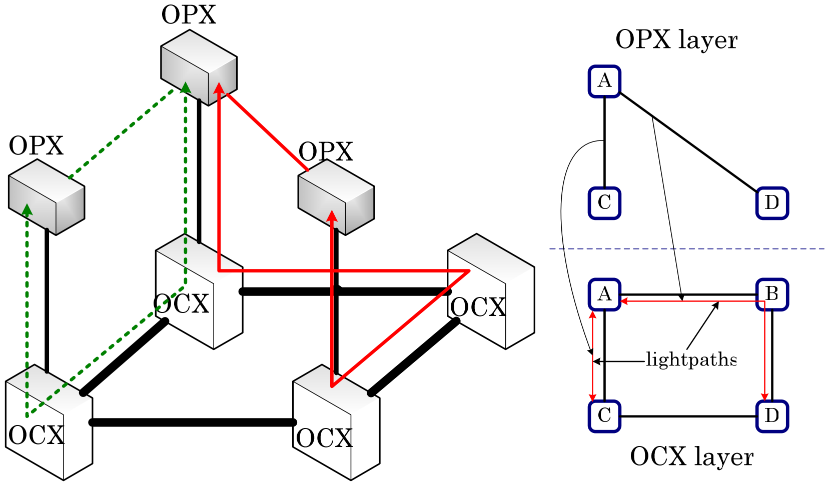


Figure 3.12. – OPS/OBS over OCS: Λ case

3. OPS/OBS uses *LCh* transport entities from the OCS layer (*LCh* case). OCS layer provides P&R, which possibly leads to fast reaction in case of failure (Figure 3.13). Since inherent restoration at the OPS/OBS layers is also active, a fault management mechanism should be implemented so as to avoid possible negative interactions between P&R schemes at different layers. For example, if the P&R at the OCS layer is not fast enough, a restoration at the OPS/OBS layer will be started. This scenario also allows arbitrary topology at the OPS/OBS layers, and hybrid MSPN.

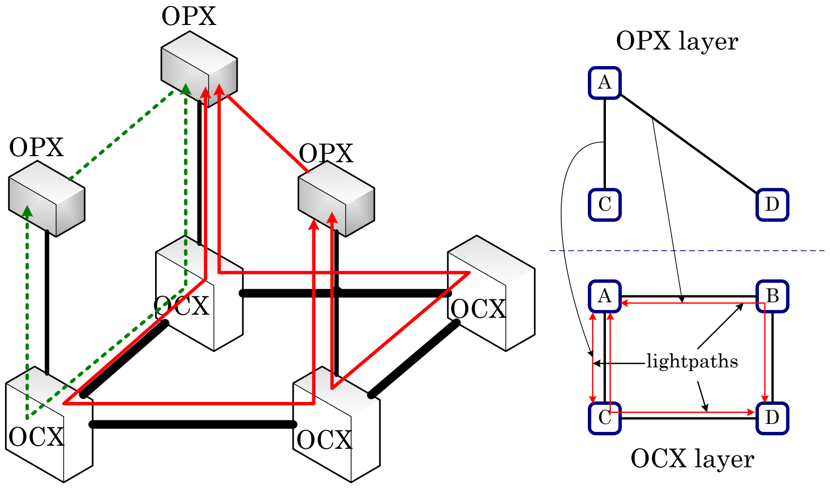


Figure 3.13. – OPS/OBS over OCS: *LCh* case

3.4. Application of Different Topological Paradigms

In the section we discuss the possibility of an application of the topological paradigms presented in the chapter 2 in the MSPN. As with the P&R paradigms, functionality is implemented in both hardware capability (i.e. possibility of switching at different layers in the architecture, at required speeds) and software that manages mapping of rules defining topological paradigm into MSPN.

MSPN supports switching at both fiber and wavelength channel layer. Obviously, through the intelligence implemented in the network management plane it is possible to apply ring topological paradigms in the MSPN. However, the question is why a network operator would implement such topological paradigm that requires for P&R purposes up to 300% of backup capacity, while flexibility of a MSPN node allows mesh and other topological paradigms. Though the answer could address speed of protection switching, the most probable cause would be scenario depicted in the Figure 3.14.

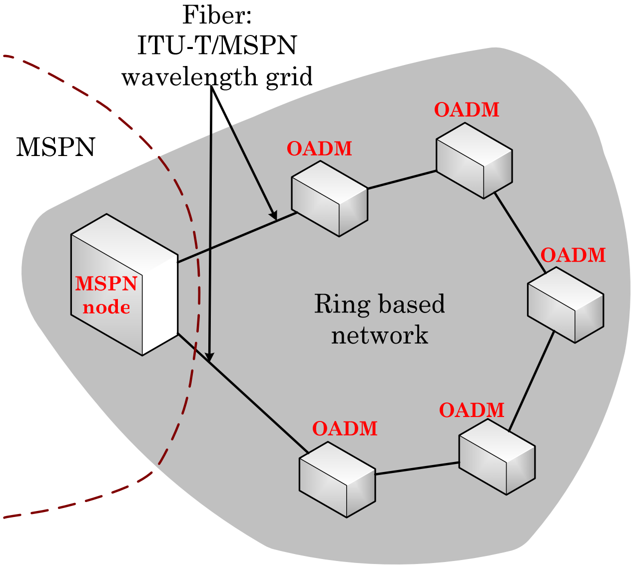


Figure 3.14. – Interconnection of MSPN and ring network

The figure shows two networks; the first is MSPN and the second one is using the ring based topological pattern. For example, this could be scenario of interconnecting two previously unconnected optical transport networks. Providing that the wavelengths on fibers connecting MSPN node with optical add/drop multiplexers (OADM) follow ITU-T wavelength grid (also a MSPN wavelength grid), MSPN node could behave like an OADM providing that;

- MSPN node supports signaling protocols used in ring network, meaning that MSPN node understands protocols used by OADMs to communicate different messages regarding various network events (provisioning, failures, etc.). In practice, this could result in both hardware and software extensions to the MSPN node.
- Network management software supports ring topological paradigm, meaning that management software knows how to react to different messages from the signaling protocols in ring network, and to implement appropriate switching positions in the MSPN node.

In the case of the mesh based topological paradigms, it is obvious that flexible architecture of a MSPN node supports all of the scenarios for the mesh networks as presented in section 2.6.2. This functionality is only implemented in the network management software responsible for switch configurations. 1+1 protection scheme is supported through the multicasting capability of a CSCIX contained in the OCX. It is also possible to support 1+1 protection through the use of a multicasting capability of a CIX switch. Main role for a multicasting capability within CIX is to support optical multicasting at the network level. Interestingly, mesh paradigm in the MSPN can be supported at both fiber and wavelength channel layer.

P-cycle paradigm is supported in the MSPN through lightpath and lightcycle transport entities. Similar to mesh, this will result in a software solution for implementing p-cycles in the MSPN. Note that p-cycle paradigm can be supported at both fiber and wavelength channel layer. In the first case, switching actions will be made within the FSX, while in latter case OCX will make necessary switching actions.

3.5. An Evolution of OTN towards MSPN

Currently, status of optical transport networks can be described as being somewhere within the range of what is shown in Figure 3.15 and Figure 3.16. Figure 3.15 basically shows point-to-point WDM systems. These systems are sometimes manually interconnected, so as to create manual lightpath between two end locations not connected directly. At the ends of such manually provisioned lightpaths, SDH DCXs, ATM switches or IP routers can be found.

The Figure 3.15 shows three such lightpath connections. This approach increases capacity of a fiber through use of DWDM (or CWDM in some cases), but does not provide additional benefits that are potentially available in the optical layer (P&R being one of them).

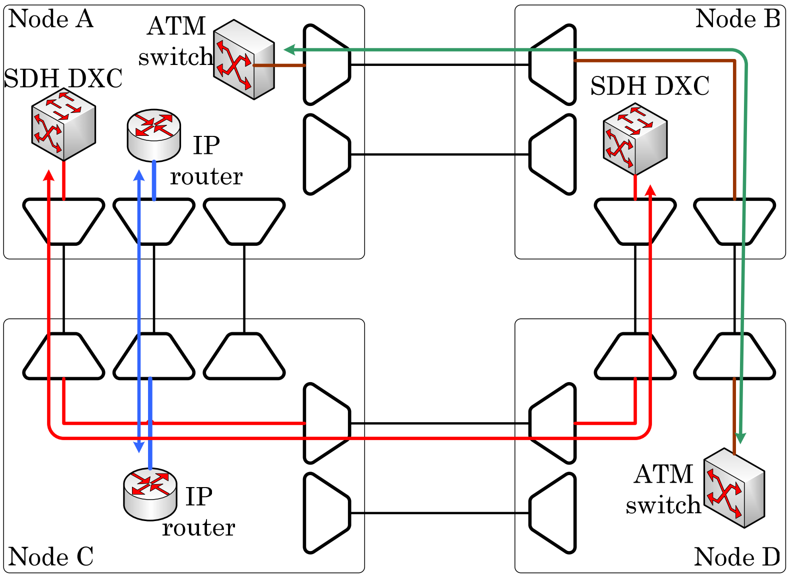


Figure 3.15. – Optical transport network – today / Scenario 1

The Figure 3.16 shows next possible step in the evolution of the WDM network. Instead of optical connectors, wavelength paths are formed either through use of optical space switches, or through use of optical add/drop multiplexers (OADM). Additional benefits are available from the optical layer, such as P&R schemes. For example, this part of the figure shows that additional lightpaths, protection ones, can be automatically configured and used in case of a failure. For some services backup lightpaths (or generally, transport entities) are not configured.

In both of the depicted scenarios, optical network provides switching at the granularity level of a wavelength channel. The concept of statistical multiplexing within the wavelength channel will surely be present one way or the other. Currently, statistical multiplexing is achieved at the level of electrical layer. More precisely, in most of the cases statistical multiplexing is carried out in IP routers. The fact is, processing limit of electronics will be reached quite soon, and then, bearing in mind that the constant request for higher processing speeds will remain, the processing should be moved into the "optical layer". This is the case for optical packet switching, or, as an intermediary step, optical burst switching.

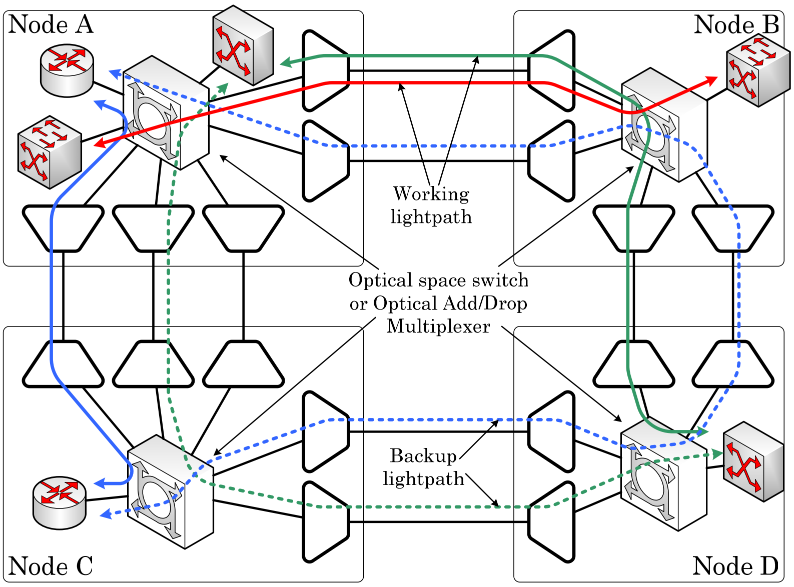


Figure 3.16. – Optical transport network - today / Scenario 2

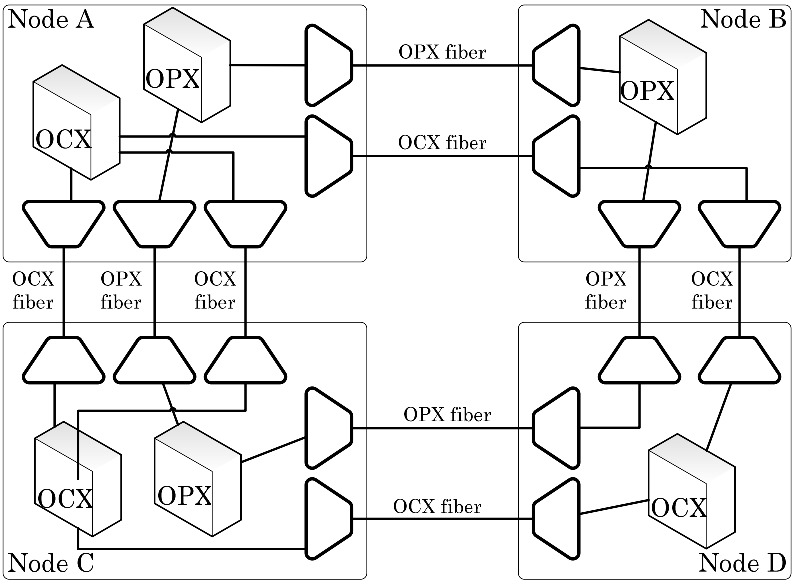


Figure 3.17. – Optical transport network – possible evolution / Step 1

If we assume that the application of optical packet/burst switching will come to life in real, production networks, sooner or later we will have situation similar to the one depicted in Figure 3.17. Two switching paradigms are present in the network, and contending for the transmission resources. In the figure, resource division granularity unit is fiber. In addition, if required, for a certain price, in terms of cost and complexity, a granularity level of wavelength channel can be used.

The problem with the OTN as depicted by Figure 3.17 is that sharing of network transmission resources by different switching paradigms is static. This means that redistribution of fibers or wavelength channels to different switching paradigms in OTN as depicted in Figure 3.17 is rather slow process due to the fact that manual intervention is required.

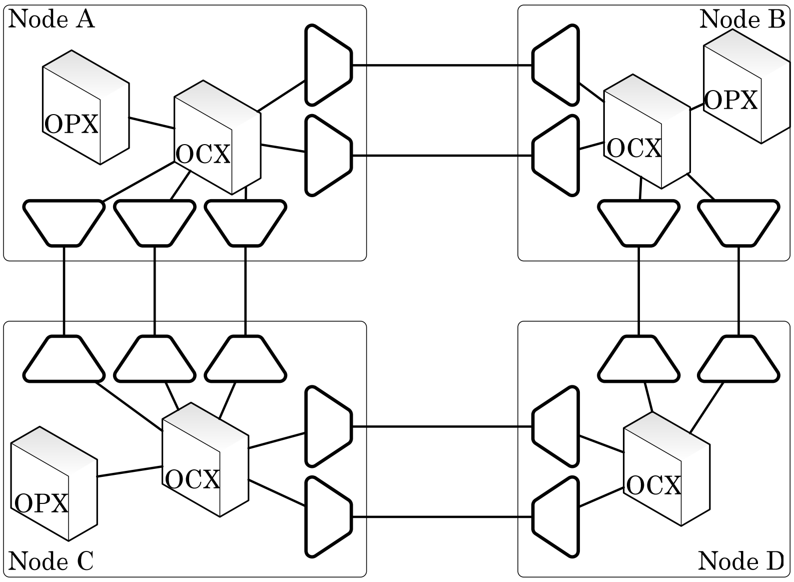


Figure 3.18. – Optical transport network – possible evolution / Step 2

Another possibility is to transfer OPS/OBS over OCX. This scenario, depicted in Figure 3.19, requires implementation of OCX at each node in an OTN, and effectively leads to the MSPN. In this scenario OCS layer enables additional P&R techniques, along with those that are inherently available in the OPS/OBS layer.

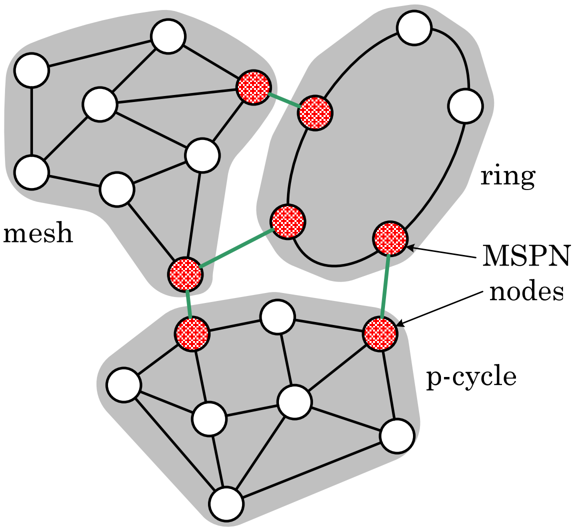


Figure 3.19. – Optical transport network – different topological paradigms

Figure 3.19 presents another issue the future optical transport networks will have to address. The figure presents scenario in which three different OTNs, using different topological paradigms, mesh, ring and p-cycle based, will eventually have to be connected to the single OTN. Certain nodes in the resulting network will have to support all of the contributing topological paradigms. In a perspective this can be viewed as a creation of OTN layer beneath of existing ones. This layer should be capable of supporting the different topological paradigms.

It seems that natural evolution of optical technology will lead to the birth of MSPN. Advances in the optical space switching technologies will lead (or already did, it is a matter of perspective) to continuing improvement of OCS switches. A good overview of different optical space switching technologies and their performances is given in [OX01]. From the overview, it is clear that even today there are available space switching technologies that enable implementation of circuit/fiber switching functionality in the MSPN node.

Further advances in the optical signal processing, optical devices such as wavelength converters, fiber delay lines, techniques of optical 3R regeneration, and finally employment of optical packet switching, or burst switching as the first step towards OPS, and their gradual implementation into existing OCS based networks, will create the need for distribution of fiber capacity between different switching paradigms. The question will arise whether to offer granularity of such division at the level of optical fiber, or wavelength channel. MSPN will offer in this context FSCI and CSCI interfaces.

Growth of traffic demands will eventually require introduction of optical services into optical transport networks. An ASON [CM01] will be first step in this direction. As of now, ASON supports only circuit switching services. A MSPN can be viewed as the next step in the evolution of ASON.

3.6. Advantages and Disadvantages of MSPN

In the section we discuss on some challenges brought upon the implementation of MSPN.

MSPN allows dynamical distribution of both fiber and wavelength capacity among different switching paradigms. The MSPN can adapt usage of transmission network resources to different traffic patterns. On the other hand, implementation of MSPN node and thus whole MSPN is of high complexity. One of the consequences of such complexity is the fact that the optical signal is passing through many optical components.

In general, the implementation of MSPN node will be possible only after the technique of 3R regeneration becomes mature. Though there are components commercially available today, out of which a MSPN node can be built, implementation is not commercially profitable.

Some of other advantages are:

- MSPN allows optical multicast through the CSCI switch in the OCX part of the node. This allows implementation of some types of O-VPN, optical multicasting and 1+1 protection scheme.
- Allows different P&R paradigms. This makes possible interconnection between OTN with different P&R paradigms.
- Allows different topological paradigms, not limited to any of them. This makes possible interconnection between OTN with different topological paradigms.
- Scalability in terms of switching paradigms. Certain functionality (OCS mainly) will have to be implemented in the ASON anyway; additional functionality can be added at any given point of time.
- OCS as architecture and technologies for its implementation are mature and well understood. The role of OCS in MSPN is; dynamic distribution of transmission resources to different switching paradigms and services, providing the circuit switched service, and finally, providing the P&R paradigms at the lower layers.
- Hybrid networks, in which different nodes support all or subset of existing switching paradigms, are supported by MSPN.

Disadvantages are:

- There are other optimal structures, in terms of cost, to implement topological paradigms. The MSPN is suboptimal due to its flexibility and complexity. On the other hand, it allows connection of OTNs with different topological paradigms through the MSPN node.

- As with the ASON itself, there is still great number of unresolved issues. For example, OPS/OBS sub-services should be defined.

We finish this chapter with the following question:

Will OPS or OBS eventually become commercially possible?

There are two possible answers to the question. The answer to that question should be viewed in the light of the fact that OCS service is next to being reality in nowadays OTNs. There are OTNs with more or less automatic provisioning of some circuit switched transport entities that were described in the chapter.

The first possible answer could be “no”. OPS/OBS will never become commercially profitable. In this case, optical networks will continue to provide OCS services only. The MSPN node structure, in the conceptual way, would still be used in the optical networks.

If the answer is “yes”, then optical network operators will have need to distribute transmission resources among different switching paradigms. Surely, this can be achieved in a manual manner, but it seems more natural to provide OPS/OBS services through OCS service. Due to the fact that complexity of OPS/OBS architecture is much higher than those of OCS, it is reasonable to infer that by the time OPS/OBS becomes commercially profitable, OCS services will be available on a dynamic basis. In other words, if OPS/OBS become reality, dynamic provisioning of OCS services, and thus ASON, will be mature. Final conclusion is that by transmission of OPS/OCS services over OCS layer will make possible dynamic distribution of transmission resources between different switching paradigms. This, in fact, is the idea of MSPN.

4. Availability Modeling

The chapter deals with the availability models of a multi-service photonic network. The term availability is one of the survivability measures used throughout the literature in order to quantitatively describe network's ability to sustain failures of its components. This is the reason why we first give an overview of the survivability measures, and formally define the term availability. Next we give an overview of the procedures used to calculate the availability of complex structures. In the last part of the chapter we present availability models for selected switching, P&R, and topological paradigms.

4.1. Survivability Measures

In general, survivability is used in the literature to denote ability of a network to provide the service in a state of internal failure. In case the service disruption occurs anyway, survivability can also refer to the ability of a network to restore its services in a fast manner.

Quantitative survivability measures are needed in order to compare different network architectures being defined in terms of switching, P&R and topological paradigms. Figure 4.1 shows classification of survivability measures. In general, survivability measures can be divided into three main classes:

- Probability based measures.
- Topological measures.
- Time measures.

Probability measures refer to a probability of an event, or probability that a given entity will be in defined state. As an example, a probability of service being available, i.e. in functional state, is possible probability measure. We can divide probability based measures into two sub-classes. We term measures in the first class as “pure” probabilistic [AV31][AV05][AV29], as they refer to a probability of a system being in functional state:

- Availability is probability that system will be functional in a given point of time,

- Reliability is probability that system will be functional during given period of time under given environmental conditions, and
- Security is probability that system will be functional, or not functional at all in a given period of time under given environmental conditions.

These are some of the pure probabilistic survivability measures. An overview of other pure probabilistic measures can be found in [AV30].

In the second case, one may be interested in the expected value of certain service parameter, for example, one of the traffic parameters, such as capacity. In [AV03] a parameter termed expected value of the available capacity (EVAC) is used. In this context, availability can be described as a probability that full service capacity will be available. It is sometimes interesting to see how much traffic will be lost. In [AV04][GN01] term expected loss of traffic (ELT), total ELT (TELT) and average ELT (AELT) are used. These measures refer to the average amount of traffic that is expected to be lost each year due to failures.

Topological measures refer to certain topological parameters that can be attributed to the ability of a network to sustain failures. For example, a node or link connectivity is a number of nodes or links respectively that have to be removed from the considered network topology in order to divide the network into two halves. Obviously, if a network posse's link connectivity of 2, it will be potentially able to survive single link failures. Actual ability of a network to sustain single link failure will depend on the applied topological, switching or P&R paradigm (or any combination of the paradigms, for that matter). An overview of topological survivability measures is given in [AV30].

Finally, the last class of the survivability measures refers to the ability of a network to respond to the failure in a goal to restore disrupted services. Depending on the generic P&R paradigm, we can have measures such as *restoration time* or *protective switching time*. These measures are function of network's underlying ability to detect failures and finally to respond to them.

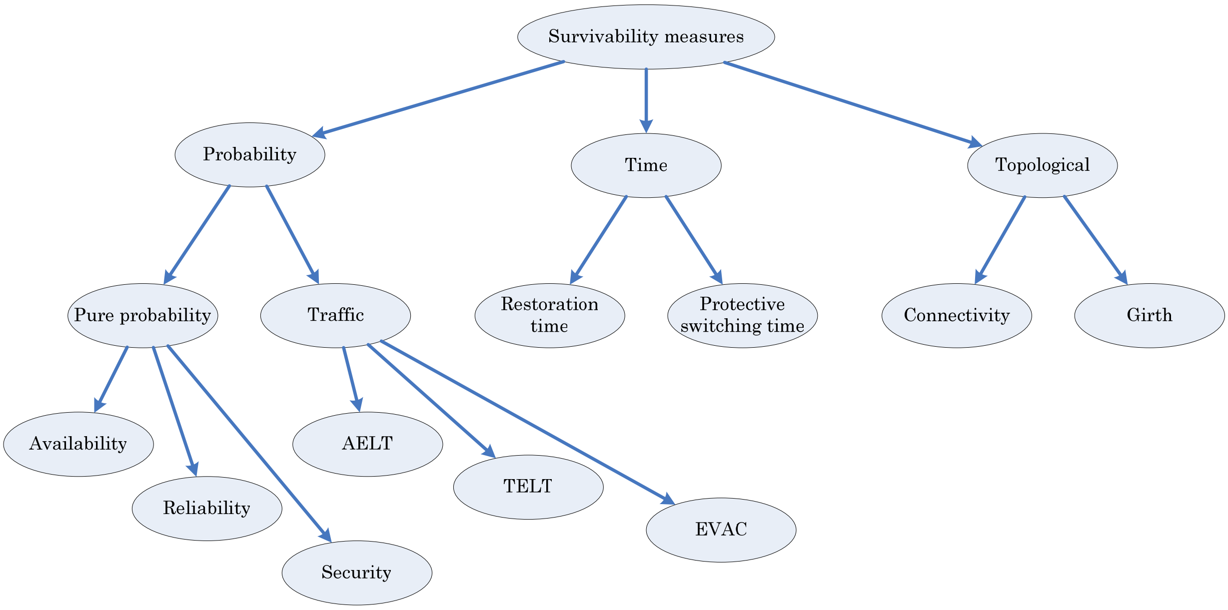


Figure 4.1. – Classification of survivability measures

In the thesis we concentrate on the availability measure. In the next section, definition of the availability measure is given.

4.2. Definition of the Availability

In [AV05] instantaneous availability of an entity is defined as the probability that an entity is in the up state at a given instant of time *t*. The steady state availability, or just availability, is defined as the limit of instantaneous availability as the time tends to infinity. If we denote instantaneous availability as $A(t)$, steady state availability is,

$$A = \lim_{t\to\infty} A(t)\,. \tag{4.1}$$

The definition of the availability allows for an entity to be repairable. If we consider non-redundant and repairable entity, then its availability can be modeled using Markov availability model, as depicted in Figure 4.2.

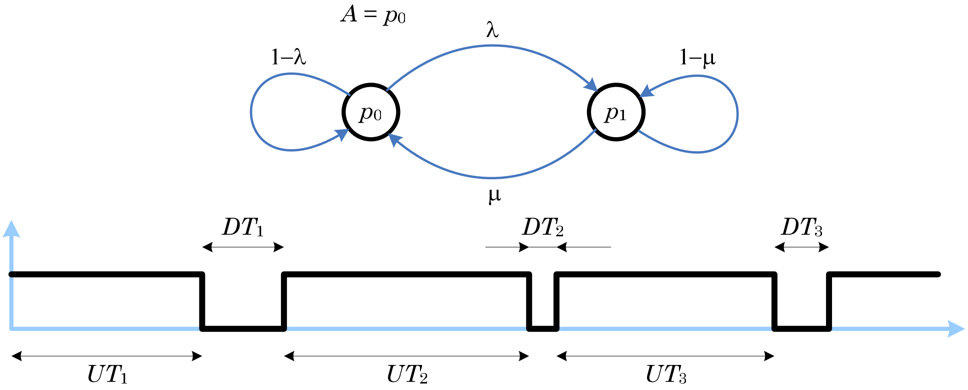


Figure 4.2. – Markov availability of a non-redundant entity

The entity is assumed to be at any instance of time in any of the two states, p_0 or p_1, referring to the functional (or up, or non-faulty) and non-functional (or down, or faulty) state. The entity's life cycle can be described as a series of changes between up and down state. Assuming that the entity is by default at the beginning of the life cycle in up state, after some time UT_1 it will broke, and enter down state. After a period of time DT_1 the entity will be repaired and enter up state once again. In the availability model the state exchanges continue indefinitely (the time is infinite).

Availability is the probability that the entity is in up state at given instance of time. In terms of up and down times it can be calculated as,

$$A = \frac{\sum_{i=1}^{\infty} UT_i}{\sum_{i=1}^{\infty} UT_i + \sum_{j=1}^{\infty} DT_j}\,. \tag{4.2}$$

Usually terms *mean up* and *mean down times* are used. They are intuitively defined as,

$$MUT = \lim_{n\to\infty} \frac{1}{n} \sum_{i=1}^{n} UT_i\,, \tag{4.3}$$

$$MDT = \lim_{n\to\infty} \frac{1}{n} \sum_{i=1}^{n} DT_i\,. \tag{4.4}$$

The availability is then,

$$A = \frac{MUT}{MDT + MUT}\,. \tag{4.5}$$

Instead of mean up and down times, terms mean time between failures (*MTBF*) and mean time to repair (*MTTR*) are usually used as they are easier to be measured by an operator. Their relation to *MUT* and *MDT* is as follows,

$$MTBF = MDT + MUT\,, \tag{4.6}$$

$$MTTR = MDT\,. \tag{4.7}$$

This is true if the measurements are taken over long period of time. The possible differences are in the fact that entity will be down due to different reasons, failure being just one of them. Another example is preventive maintenance action. In the thesis we assume that down times are dominantly caused by failures.

In the literature the term mean time to failure (*MTTF*) is often used. The *MTTF* is simply,

$$MTTF = MUT\,. \tag{4.8}$$

In a probabilistic approach, availability models use two random variables denoting times to failure, and repair times. In most of the literature exponential distribution of these times is assumed. Due to the fact that exponential distribution is defined by the mean value, in the case of availability models mean values represent *MTTF* and *MTTR*. Instead of times, a notion of intensity is often used in probabilistic availability models. Failure intensity or failure rate λ, and repair intensity or repair rate μ are related to *MTTF* and *MTTR* in the following way,

$$\lambda = \frac{1}{MTTF}\,, \tag{4.9}$$

$$\mu = \frac{1}{MTTR}\,. \tag{4.10}$$

In terms of failure and repair rates, availability of an entity can be expressed as,

$$A = \frac{\mu}{\mu + \lambda}\,. \tag{4.11}$$

Typically, in the telecommunication systems failure rates are much lower than repair rates,

$$\lambda \ll \mu\,, \tag{4.12}$$

and this leads to availability figures close to 1. For the presentation purposes a notion of unavailability (*U*) is used, which is defined as the complementary measure,

$$U = 1 - A\,. \tag{4.13}$$

In terms of failure and repair rate, unavailability is equal to,

$$U = \frac{\lambda}{\mu + \lambda} \approx \frac{\lambda}{\mu}\,. \tag{4.14}$$

Strictly speaking, expressions (4.11) and (4.14) assume exponential distribution of failure and repair times. As presented, constant failure intensity/rate is assumed. In some case it is also useful to assume failure rate that is changing in time, lowering or raising. In this regard Rayleigh and Weibull distribution functions can be used for failure times. In the thesis we always assume exponential distribution of both failure and repair times.

In the thesis we distinguish two classes of entities regarding their availability calculation:

- Simple entity. The entity is defined by the distribution of failure and repair time. Equations presented above, (4.11) and (4.14), can be used to calculate availability of unavailability of the entity. In the thesis simple components are photonic devices, for example optical amplifiers, multiplexers, de-multiplexers. We assume exponential distributions of both failure and repair times. Consequently, distributions are defined by the mean values of respective times.

- Complex entity. The entity is defined by the logical expression defining non-faulty state of an entity. Logical expressions contain any combination of logical expressions defining other complex entities, and simple entities. In the thesis complex entities are transport entities through which network is providing service to its clients.

This section explained the availability calculation for the simple entity. In the next section an overview of the calculation procedures used to calculate availability of entity defined by the arbitrarily complex logical expression.

4.3. Procedures for Availability Calculation

Fundamental to the calculation of availability is the representation of simple entity non-faulty state as an event x_i. In the availability modeling, an entity can be in any of the two states: non-faulty (failure-free), or faulty. Faulty state of the component *i* is the complement of the non-faulty state of the component, in the thesis denoted as $\overline{x_i}$. Following expression holds,

$$x_i \cup \overline{x_i} = 1,$$

meaning that the left side of the expression covers all possible states of a component *i*. In the set theory, on the right side of the expression the complete set of events Ω (sample space, universal set, all possibilities) would be placed, e.g. all possible states of a simple entity. Operator $\cup$ is the union operator. In the context of probability theory universal set is also termed certain event.

Probability that the system is in the non-faulty state is by the definition availability,

$$A_i = \Pr\{x_i\},$$

while probability that a simple entity is in the faulty state is by the definition unavailability,

$$U_i = \Pr\{\overline{x_i}\}.$$

Since the probability of a certain event is,

$$\Pr\{\Omega\} = 1,$$

and since two events denoting non-faulty and faulty state of a simple entity are disjoint, or

$$x_i \cap \overline{x_i} = 0,$$

where $\cap$ is intersection operator, the following expression is valid,

$$\Pr\{\Omega\} = \Pr\{x_i \cup \overline{x_i}\} = \Pr\{x_i\} + \Pr\{\overline{x_i}\} = A_i + U_i = 1.$$

Due to the fact that entities can be in two possible states, we refer to the events x_i as logical (or Boolean) variables. The state of a complex entity *e* can also be non-faulty and faulty, and it is defined using notions of a Boolean algebra. We will refer to the expressions identifying relationship between complex entity state and other entities, complex or simple, as logical expressions. The union operator from the set theory can be viewed as logical OR operator in the Boolean algebra, while intersection operator can be viewed as a logical AND operator in the Boolean algebra.

In the thesis logical expressions defining non-faulty state of a complex entity are always developed into the form of union of product terms,

$$LE(e) = \bigcup_{\forall PT \in e} \left(\bigcap_{\forall i \in PT} x_i \right) \tag{4.15}$$

where $LE(e)$ is logical expression defining non-faulty state of an entity e, PT is a product term, and x_i is a simple entity. The form is obtained by evaluating arbitrarily complex logical expression that may contain other logical expressions as well.

As an example, consider an optical transmission system as depicted in Figure 4.3, and two wavelength channels, defined for the opposite directions, that are part of the logical channel.

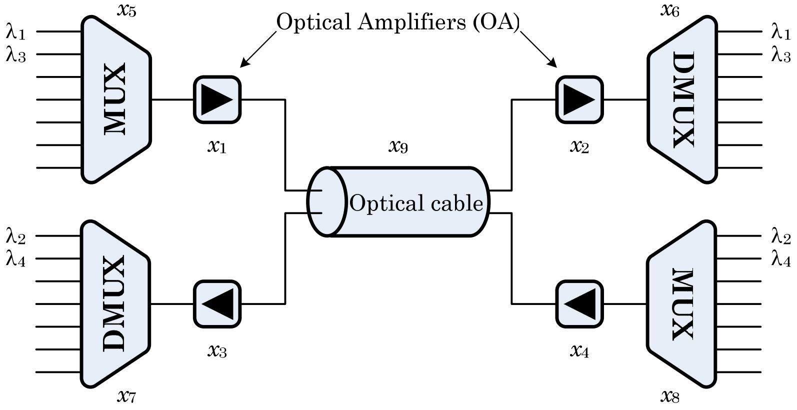


Figure 4.3. – An example of DWDM link availability modeling

Each physical component is in the context of availability calculation referred to as simple entity. Failure rates and mean times to repair for each type of physical component are defined. By using these values an availability of a simple entity can be calculated.

Furthermore, each simple entity is represented by logical (or Boolean) variable x_i, as denoted in the figure. The variable denotes whether the corresponding physical component is in the failure of failure-free state.

Now we can define two logical expressions defining non-faulty state of a complex entities referring to wavelength channels λ_1 and λ_2 (note that these are not wavelengths, but wavelength channels instead),

$$LE(\lambda_1) = x_5 \cap x_1 \cap x_9 \cap x_2 \cap x_6,$$

$$LE(\lambda_2) = x_8 \cap x_4 \cap x_9 \cap x_3 \cap x_7.$$

For example, wavelength channel λ_1 will be in non-faulty state if all of the components corresponding to the logical variables contained within logical expression are also in the non-faulty state (there is an AND relationship between the state of the components).

Each of the two logical expressions can be viewed as a path between end points of corresponding wavelength channel. Clearly, path defines AND relationship between logical variables. Communication using the path will be non-faulty if all of its elements are non-faulty. In certain cases it is simpler to represent the logical expression by corresponding logical structure, which we term in the thesis *availability structure*. The availability structure consists of at least two nodes, source (*s*) and termination (*t*). These nodes are considered virtual due to the fact that they do not take part in the logical expression, but instead define starting and ending nodes for a path (paths) that refers to a product term (terms). For both wavelength channels single path exists between nodes *s* and *t*, and thus logical expressions defining state of wavelength channels are single termed (Figure 4.4).

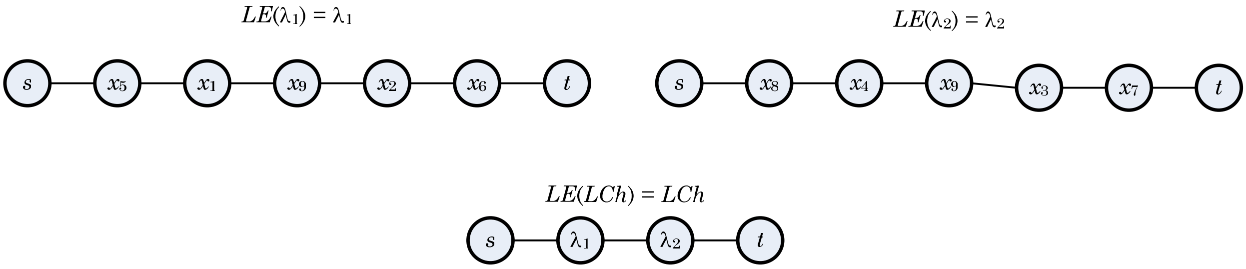


Figure 4.4. – Availability structures for wavelength channels and logical channel

Logical expression defining non-faulty state of the logical channel composed of two wavelength channels is a complex logical expression containing two other complex logical expressions,

$$LE(LCh) = LE(\lambda_1) \cap LE(\lambda_2).$$

The logical channel will be non-faulty, e.g. available, if both of the wavelength channels contained within are non-faulty. Figure 4.4 also shows availability structure for the logical channel.

After evaluating the expression by using axioms of Boolean algebra we obtain single product term,

$$LE(LCh) = x_5 \cap x_1 \cap x_9 \cap x_2 \cap x_6 \cap x_8 \cap x_4 \cap x_3 \cap x_7.$$

Assuming that all logical variables are independent, probability of the logical expression, availability, is,

$$A(LCh) = A_5 \cdot A_1 \cdot A_9 \cdot A_2 \cdot A_6 \cdot A_8 \cdot A_4 \cdot A_3 \cdot A_7.$$

Now consider logical channel with 1+1 protection on the level of wavelength channel between nodes *A* and *F* as shown in Figure 4.5. Wavelength channel pairs (two directions) are routed over node and link independent paths. In the example logical variables x_i refer to optical cables on corresponding links.

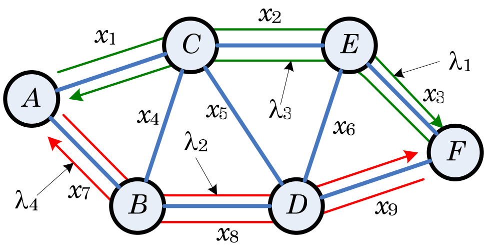


Figure 4.5. – An example of availability modeling for a 1+1 protection in mesh network

The logical channel is composed of two wavelength channels per direction; λ_1 and λ_3 in one direction, λ_2 and λ_4 in other direction,

$$LE(LCh) = (\lambda_1 \cap \lambda_3) \cup (\lambda_2 \cap \lambda_4).$$

Availability structure for this case is shown in Figure 4.6. In the availability structure, entities with logical OR relationship are drawn in parallel.

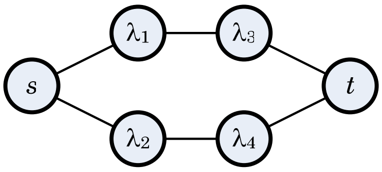


Figure 4.6. – Availability structure for 1+1 protection

From the Figure 4.6 following expressions can be drawn,

$$\lambda_1 = \lambda_3 = x_1 \cap x_2 \cap x_3,$$

$$\lambda_2 = \lambda_4 = x_7 \cap x_8 \cap x_9.$$

Fully developed, the expression for logical channel becomes,

$$LE(LCh) = \left[(x_1 \cap x_2 \cap x_3) \cap (x_1 \cap x_2 \cap x_3) \right] \cup \left[(x_7 \cap x_8 \cap x_9) \cap (x_7 \cap x_8 \cap x_9) \right],$$

$$\begin{aligned} LE(LCh) = {} & (x_1 \cap x_2 \cap x_3) \cup \\ & (x_7 \cap x_8 \cap x_9) \end{aligned} . \tag{4.16}$$

The union of product terms in the expression above is not disjoint, since there are no complemented logical variables in the expression. Consequently, probability is not simply a sum of product term probabilities,

$$A(e) = \Pr\{LE(e)\} = \Pr\left\{ \bigcup_{\forall PT \in e} \left(\bigcap_{\forall i \in PT} x_i \right) \right\} \neq \sum_{\forall PT \in e} \Pr\left\{ \bigcap_{\forall i \in PT} x_i \right\} = \sum_{\forall PT \in e} \prod_{\forall i \in PT} A_i . \tag{4.17}$$

The inequality in the expression is the major obstacle in calculating the availability of complex entity. In the case of MSPN (or any optical transport network for that matter), the number of logical variables (e.g. physical components) can be up to several thousands. This leads to high number of product terms in the union describing complex entity (for example, logical connection). For example, the number of product terms in the union can be as high as 10 000 [AV15]. The process of developing such expressions is both time and space (memory) consuming.

In the availability calculation procedure, the main problem is to calculate the probability of logical expression defining non-faulty state of a complex entity. In general, there are two main classes of procedures used to calculate probability of a logical expression;

- Analytical, and
- Simulation.

In an analytical procedure the central part is conversion of non-disjoint union of product terms into a disjoint one. Availabilities of simple entities are treated as probabilities. Therefore, procedures can be applied to calculate other probabilistic survivability measures (such as reliability).

In the simulation, each simple entity is represented with two random variables denoting failure and repair times. Any simulation that uses random variables is known as Monte-Carlo simulation.

4.3.1. Analytical Procedures

The central problem in the analytical procedure is related to the conversion of generally non-disjoint union of product terms into a disjoint one, so that the probability of the logical expression can be calculated as a simple sum of product term availabilities.

Consider a logical expression in the union of product terms,

$$LE(e) = \bigcup_{\forall PT \in e} \left(\bigcap_{\forall i \in PT} x_i \right), \tag{4.18}$$

where product terms are in the form,

$$PT = \bigcap_{\forall i \in PT} x_i . \tag{4.19}$$

Due to the assumption that logical variables representing component states are independent, availability (or probability) of a product term is,

$$A(PT) = \Pr\{PT\} = \prod_{\forall i \in PT} A_i , \tag{4.20}$$

where A_i is the availability of a component i.

The union of product term in expression (4.18) is non-disjoint. The following should be valid in order to have disjoint union of product terms,

$$PT_i \cap PT_j = 0 \text{ for } \forall PT_i, PT_j \in LE(e), PT_i \neq PT_j$$

In the case the union of product terms is disjoint, inequality in the expression (4.17) becomes equality,

$$A(e) = \Pr\{LE(e)\} = \sum_{\forall PT \in e} \prod_{\forall i \in PT} A_i .$$

A remark should be made concerning the assumption of the independence between logical variables corresponding to physical components. In most cases this is true, as failure in one component would not cause failure in another. However, there are exceptions;

- Natural disasters, such as earthquakes and floods. Clearly, such natural events would cause failures in all physical components located in the affected geographical area. We assume that the probability of such event can be neglected.
- In some cases it is possible for a component failure to trigger failures in other components. For example, failure in an optical amplifier, and excessive optical power on the output of the amplifier can in some cases damage components that are directly or indirectly connected to the output of a such component. We also do not consider possibility of such event.

General to all the analytical procedures is use of De-Morgans laws [AV16][AV17],

$$\overline{\left(\bigcap_{i=1}^{n} x_i \right)} = \bigcup_{i=1}^{n} \overline{x_i} , \tag{4.21}$$

$$\overline{\left(\bigcup_{i=1}^{n} x_i \right)} = \bigcap_{i=1}^{n} \overline{x_i} . \tag{4.22}$$

Based on the manner in which De-Morgan laws are used, we can further divide analytical procedures in two classes;

- Sum of disjoint product terms (SDPT).
- Terminal Pair Availability (TPA).

In the first class of analytical procedures, De-Morgan laws are used to convert sum of non-disjoint product terms into a disjoint one. In the second case, sum of non-disjoint product terms is represented in a compressed format, as an availability structure (or graph for that matter) and TPA algorithms are applied to the availability structure.

4.3.1.1. Sum of Disjoint Product Terms

The main idea behind the algorithms that create sum of disjoint product terms out of non-disjoint union can be explained on a simple example. Consider a simple union of non-disjoint product terms,

$$LE = (x_1 \cap x_2) \cup (x_3 \cap x_4).$$

De-Morgan laws can be modified into following form [AV06],

$$\overline{x_1 \cap x_2} = \overline{x_1} \cup \left(x_1 \cap \overline{x_2}\right), \tag{4.23}$$

$$\overline{\overline{x_1} \cap \overline{x_2}} = x_1 \cup \left(\overline{x_1} \cap x_2\right). \tag{4.24}$$

Due to the fact that the intersection of an event *e* with certain event Ω yields an event *e*,

$$e \cap 1 = e,$$

we can use following identity to modify starting union of non-disjoint terms,

$$LE = \left[(x_1 \cap x_2) \cup (x_3 \cap x_4)\right] \cap 1. \tag{4.25}$$

Certain event can be represented in the following way,

$$1 = (x_1 \cap x_2) \cup \left(\overline{x_1 \cap x_2}\right),$$

and by applying De-Morgan law as in (4.23) we obtain,

$$1 = (x_1 \cap x_2) \cup \left(\overline{x_1}\right) \cup \left(x_1 \cap \overline{x_2}\right). \tag{4.26}$$

Now (4.26) is placed into (4.25) and we obtain,

$$LE = \left[(x_1 \cap x_2) \cup (x_3 \cap x_4)\right] \cap \left[(x_1 \cap x_2) \cup \left(\overline{x_1}\right) \cup \left(x_1 \cap \overline{x_2}\right)\right]. \tag{4.27}$$

Distribution laws in the set algebra are valid for both union and intersection operators. If the distribution law is applied to the intersection operator between two square bracket, (4.27) becomes,

$$\begin{aligned} LE = {} & (x_1 \cap x_2 \cap x_1 \cap x_2) \cup \\ & \left(x_1 \cap x_2 \cap \overline{x_1}\right) \cup \\ & \left(x_1 \cap x_2 \cap x_1 \cap \overline{x_2}\right) \cup \\ & (x_3 \cap x_4 \cap x_1 \cap x_2) \cup \\ & \left(x_3 \cap x_4 \cap \overline{x_1}\right) \cup \\ & \left(x_3 \cap x_4 \cap x_1 \cap \overline{x_2}\right) \end{aligned}. \tag{4.28}$$

By using following identities,

$$x_i \cap x_i = x_i,$$

$x_i \cap 0 = 0$, and

$$x_i \cap \overline{x_i} = 1,$$

expression (4.28) becomes,

$$LE = (x_1 \cap x_2) \cup (x_3 \cap x_4 \cap x_1 \cap x_2) \cup \left(x_3 \cap x_4 \cap \overline{x_1}\right) \cup \left(x_3 \cap x_4 \cap x_1 \cap \overline{x_2}\right). \tag{4.29}$$

Finally, first two product terms in the (4.29) can be written as,

$$(x_1 \cap x_2) \cup (x_3 \cap x_4 \cap x_1 \cap x_2) = (x_1 \cap x_2) \cap \left[1 \cup (x_3 \cap x_4)\right]. \tag{4.30}$$

Since,

$$1 \cup x_i = 1,$$

(4.30) becomes,

$$(x_1 \cap x_2) \cup (x_3 \cap x_4 \cap x_1 \cap x_2) = (x_1 \cap x_2).$$

The final conversion is as follows,

$$LE = (x_1 \cap x_2) \cup \left(x_3 \cap x_4 \cap \overline{x_1}\right) \cup \left(x_3 \cap x_4 \cap x_1 \cap \overline{x_2}\right).$$

Note that all product terms in the union are disjoint. The explained procedure should be applied recursively until all product terms in the union are disjoint.

The probability of the logical expression is sum of product term availabilities. In this case, this would be,

$$A(LE) = A_1 \cdot A_2 + A_3 \cdot A_4 \cdot U_1 + A_3 \cdot A_4 \cdot A_1 \cdot U_2.$$

Events in each product terms are independent, due to the rule that says,

if x_i and x_j are independent, $\Rightarrow$ $\overline{x_i}$ and x_j are independent.

In this class of analytical algorithms, the algorithm of Abraham described in [AV18] is a good representative. Further improvements are presented in [AV19]. The problem with the Abraham-like algorithms is the fact that they create union of disjoint terms that largely exceeds the starting non-disjoint union. In many cases, the conversion becomes intractable due to space constraints. In [AV20] and [AV21] minimization of union of non-disjoint product terms is presented that further reduces space and time computational complexity. In [AV22] errors in previous work [AV20][AV21] have been corrected.

In [AV15] enhancements to the original Abraham algorithm are introduced. Where possible, the analytical results presented in the thesis are obtained using enhanced version of Abraham algorithm.

Disadvantage of the SDP algorithms is that they work with union of product terms, which is for problems of practical size, in most cases, demanding in terms of space (computer memory). This fact makes impossible parallel creation of disjoint union of product terms defining non-faulty $LE(e)$ and faulty state $LE(\bar{e})$ of an entity *e*. Due to the fact that,

$$LE(e) \cup LE(\bar{e}) = 1,$$

it follows that,

$$\Pr\left\{LE(e)\right\} + \Pr\left\{LE(\bar{e})\right\} = A(e) + U(e) = 1.$$

Thus, an approximate calculation using the fact,

$$\varepsilon \ll \left|1 - A(e) - U(e)\right|$$

is also practically impossible.

Additional enhancements to the original Abraham algorithm are presented in [AV20]. [AV21][AV22].

4.3.1.2. Terminal Pair Availability

Instead of using sum of non-disjoint product terms, terminal pair availability algorithms are applied to the availability structure. In general, De-Morgan laws are used to create universal set, e.g. to cover all possible cases. The principle is explained using the same logical expression as in the case of SDPT algorithms,

$$LE = (x_1 \cap x_2) \cup (x_3 \cap x_4).$$

This logical expression can be represented by the availability structure as shown in Figure 4.7. In terms of availability structure, logical expression will be available (non-faulty) if there is a path composed of non-faulty entities. In the SDTP case, the enumeration of all paths between nodes *s* and *t* would yield union of product term, in which each path would represent single product term.

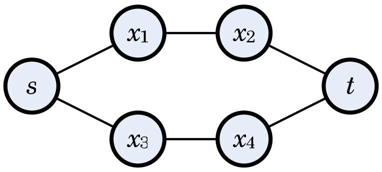


Figure 4.7. – Availability structure for the principle explanation of TPA

There are two classes of TPA algorithms:

- Shortest path based, and
- Minimal cut based.

The principle of a TPA algorithm for both cases is the same, except that in the first case paths are used, and this class of TPA works inherently with the availability of an entity. In the second class, cuts are analyzed, and their probability, and thus this class of algorithms work with the unavailability of an event.

We will explain the principle on the example of first class of algorithms. The shortest path between nodes *s* and *t* can be viewed as an event defining non-faulty state of a complex entity represented by the availability structure. We denote this event as,

$$ev_1 = x_1 \cap x_2,$$

and place the event into the set of events corresponding to a non-faulty state of a complex entity. The set is denoted as *SE* (as in successful events),

$$SE = \{ev_1\}.$$

Event $x_1 \cap x_2$ defines non-faulty state of an complex entity, since there is path available between nodes *s* and *t* in the availability structure, passing over components x_1 and x_2. The probability of the event can be simply calculated as,

$$\Pr\{x_1 \cap x_2\} = A_1 \cdot A_2.$$

In order to cover all possibilities, i.e. universal set, we have to complement starting event,

$$(x_1 \cap x_2) \cup \overline{(x_1 \cap x_2)} = 1. \tag{4.31}$$

Now we use modified De-Morgan formula (4.23) to further develop product term on the right of the expression (4.31),

$$\overline{\left(x_1 \cap x_2\right)} = \left(\overline{x_1}\right) \cup \left(x_1 \cap \overline{x_2}\right). \tag{4.32}$$

Each product term in the union on the right side of the equality sign in (4.32) represents an sub-event that can define either non-faulty or faulty state of a complex entity, depending on the fact whether there is a path between nodes *s* and *t*. In this example, there are paths still available. New events are,

$$ev_2 = \overline{x_1} \cap x_3 \cap x_4 ,$$

$$ev_3 = x_1 \cap \overline{x_2} \cap x_3 \cap x_4 .$$

Both of these events are successful and placed into set *SE*,

$$SE = \left\{ev_1, ev_2, ev_3\right\}.$$

Note that these possibilities do not define all the possible events. Events ev_2 and ev_3 need to be further developed in order to create universal set,

$$\overline{x_1} \cap \left\{\left(x_3 \cap x_4\right) \cup \overline{\left(x_3 \cap x_4\right)}\right\} = \left(\overline{x_1} \cap x_3 \cap x_4\right) \cup \left(\overline{x_1} \cap \overline{x_3 \cap x_4}\right), \tag{4.33}$$

$$x_1 \cap \overline{x_2} \cap \left\{\left(x_3 \cap x_4\right) \cup \overline{\left(x_3 \cap x_4\right)}\right\} = \left(x_1 \cap \overline{x_2} \cap x_3 \cap x_4\right) \cup \left(x_1 \cap \overline{x_2} \cap \overline{x_3 \cap x_4}\right). \tag{4.34}$$

Application of modified De-Morgan law to the product term on the right side of expressions (4.33) and (4.34), leads to,

$$\left(\overline{x_1} \cap \overline{x_3 \cap x_4}\right) = \left(\overline{x_1} \cap \overline{x_3}\right) \cup \left(\overline{x_1} \cap x_3 \cap \overline{x_4}\right),$$

$$\left(x_1 \cap \overline{x_2} \cap \overline{x_3 \cap x_4}\right) = \left(x_1 \cap \overline{x_2} \cap \overline{x_3}\right) \cup \left(x_1 \cap \overline{x_2} \cap x_3 \cap \overline{x_4}\right).$$

Four new events are generated,

$$ev_4 = \overline{x_1} \cap \overline{x_3} ,$$

$$ev_5 = \overline{x_1} \cap x_3 \cap \overline{x_4} ,$$

$$ev_6 = x_1 \cap \overline{x_2} \cap \overline{x_3} ,$$

$$ev_7 = x_1 \cap \overline{x_2} \cap x_3 \cap \overline{x_4} .$$

All the events represent faulty state of a complex entity, and they can not be developed further. They are placed in the set of events defining unsuccessful events, *UE*,

$$UE = \left\{ev_4, ev_5, ev_6, ev_7\right\}$$

The universal set is thus,

$$\Omega = \left\{ev_1, ev_2, ev_3, ev_4, ev_5, ev_6, ev_7,\right\} = SE \cup UE .$$

Note that all the events in the Ω are disjoint. The availability can be calculated as,

$$A(LE) = \sum_{\forall ev_i \in SE} \Pr\left\{ev_i\right\},$$

and unavailability is,

$$U(LE) = \sum_{\forall ev_i \in UE} \Pr\left\{ev_i\right\}.$$

Probability of a product term is,

$$\Pr\{ev_i\} = \left(\prod_{\forall x_i \in ev_i} A_i\right) \cdot \left(\prod_{\forall \overline{x}_i \in ev_i} U_i\right).$$

In comparison to SDPT algorithms, this class of availability calculation algorithms has following advantages;

- They work with the availability structure which can be viewed as a compressed union of non-disjoint product terms.
- As the algorithms recursively enumerate successful and unsuccessful events, partial availability and unavailability can be calculated. Thus they inherently support approximate calculation that can be stopped as soon as acceptable level of precision ε is reached, $\varepsilon \ll |1 - A(e) - U(e)|$.

The Figure 4.8 shows classification of TPA algorithms [AV11]. There are two main classes of the TPA algorithms depending on the way the partitioning is made.

In the first class, the goal is to establish communication, for example by using shortest paths. This is the shortest paths partitioning class of TPA algorithms. The example above showed shortest path partitioning TPA algorithm. Examples of this class of algorithms are Dotson/Gobien algorithm (DG, [AV07]) and modified Dotson (MD, [AV08])]. The original DG and MD algorithm do not consider node availabilities. Node pair reliability (NPR [AV10]) algorithm includes node availabilities in link availabilities. Terminal pair reliability algorithm (TPR, [AV14]) works with node availabilities. Other examples of TPA algorithms based on shortest path partitioning are terminal pair availability (TPA, [AV11]), Evaluating Network Reliability (ENR, [AV09]) and Fast Terminal Pair Availability (FTPA, [AV11]).

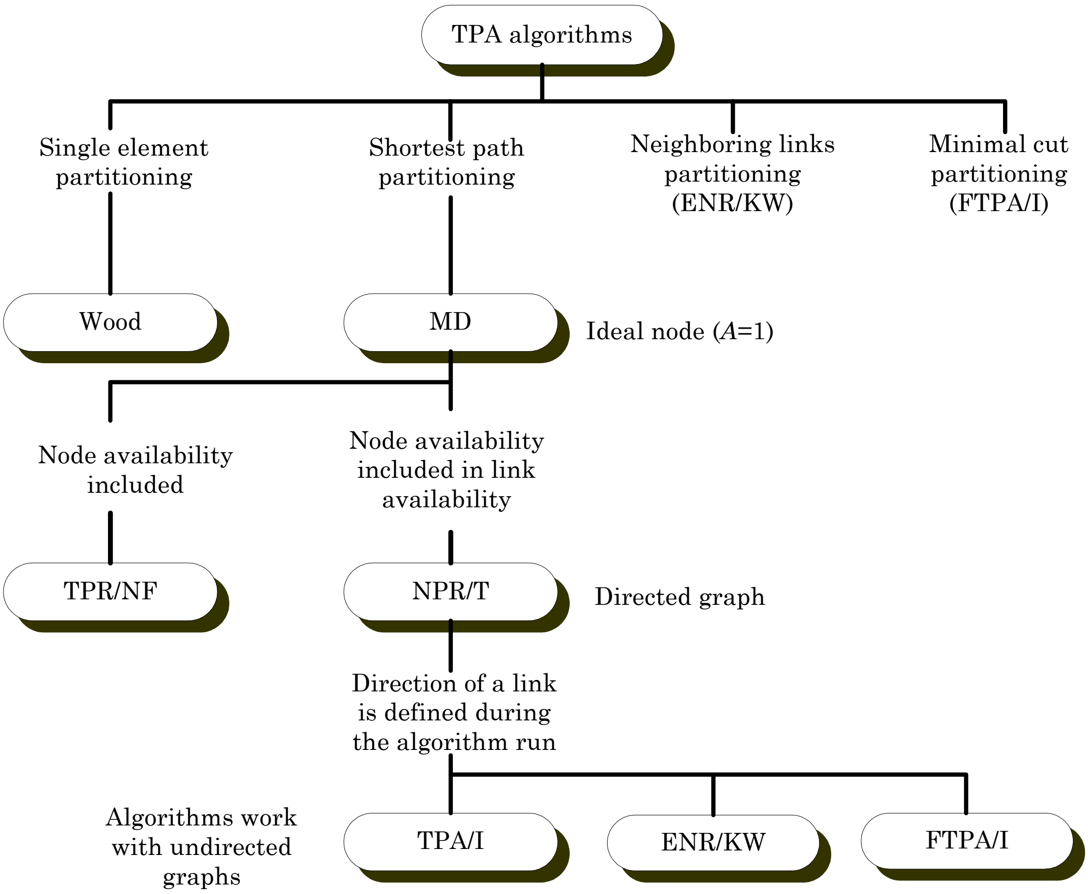


Figure 4.8. – Classification of TPA algorithms

The second class of TPA algorithms is based on the disruption of communication, i.e. partitioning based on cut is used. The second class of TPA algorithms can be furthermore divided into algorithms that use partitioning based on neighboring links [AV09], and algorithms that use minimal cut partitioning (FTPA, [AV11]). The advantage of the latter is in the minimal number of disjoint events in the universal set generated by the partitioning scheme. However, the problem is finding of a minimal cut. The advantage of the first subclass in that it does not require finding of a minimal cut.

4.3.2. Monte-Carlo Simulation

The number of physical components, and therefore logical variables, is determined by the architecture of the network and size of the network. Complexity of the availability analysis, in terms of both space and time, depends on the number of logical variables in the logical expression defining non-faulty state of a complex entity. Analytical procedures do not behave well as the number of logical variables increases, meaning that in the best case computation time almost exponentially grows with the number of logical variables. This fact makes the application of analytical procedures to some architectural scenarios impossible due to the space and time constraints (i.e. computer memory).

In the case that application of analytical procedures fails, Monte-Carlo simulation represents the only possible solution. Although the Monte-Carlo simulation can be time consuming, the space complexity is not an issue due to the fact that for each logical variable only limited resources in terms of computer memory are required.

In the Monte-Carlo simulation of availability, complex entity non-faulty state can be described by either;

- Sum of non-disjoint product terms, or
- Availability structure.

Monte-Carlo simulation of availability simulates the life cycle of a complex entity under analysis. The life cycle of a complex entity is composed of simulation events representing the change of state in any of the simple entity. These are either failures or repairs of simple entities.

At the beginning of the simulation, all simple entities are non-faulty. Times to failures are generated randomly, according to predefined distribution, for each of the simple entities. These are actually simulation events. Simulation heap takes car that simulation events are “executed” in order of the increasing simulation time. After each simulation event, state of a complex entity is determined by using sum of non-disjoint product terms, or availability structure. An “execution” of a simulation event means calculation of time for a next simulation event to appear for a simple entity under question. If the simple entity is in non-faulty state, then time to failure is generated. Otherwise, the time to repair is generated.

The consequence of the description of Monte-Carlo simulation is that for each logical variable only a simulated time to the next event, failure or repair, need to be memorized. Hence, space complexity of the Mont-Carlo simulation linearly depends on the number of logical variables.

4.4. Availability Models

In this section we start with the presentation of two examples for availability modeling. In the first case, simple WDM point-to-point WDM transmission link is considered, with different design options, and under assumption of the same total capacity [AV03]. In the availability analysis, transmitters are identified as critical components. This was the reason why in the second case, an availability model for a WDM transmission link with 1:N protection sharing was analyzed. The protection is implemented at the level of wavelength channels, i.e. spare transmitters were used.

The rest of the section introduces availability models for optical circuit switched networks, and optical packet switched networks. Due to the fact that optical transport network is providing its services to clients through transport entities, presented availability models are also defined in the context of transport entities. In the case of optical circuit switched networks, developed availability models are for transport entities defined in the chapter 3. The only exception was wavelength channel group transport entity, which was not analyzed in the thesis. In the case of optical packet switching network, new transport entities, used in the availability analysis are defined.

The availability analysis of the optical transport network assumes that optical network is completely defined. This requires procedure for network design. Procedures for network design used to completely define optical network are described in chapter 5. This is the reason why in this chapter only availability models were presented, and availability analysis results are given after the network design procedures have been described, in chapter 6.

4.4.1. Optical Circuit Switching

4.4.1.1. WDM Transmission link

The section describes a comparison of availability between two point-to-point WDM transmission systems of identical capacities, but different number of channels. The intention is to create a simple availability model to be used in determining the availability values of critical optical components. Because of the uncertainty of optical component failure rate data, the comparison is done over a range of values.

In the comparison we assume that critical components, as far as availability is concerned, are transmitters and laser pumps, which are the most critical components in optical amplifiers. In order to make the comparison easier, the structures of optical amplifiers are simplified without loosing realistic view of the influence of component availability on the availability of entire transmission system.

The comparison is made by equalizing the availability performances for compared cases, and drawing a function of transmitter availability versus laser pump availability. Consequently, a range of laser pump availability values will generate the range of transmitter values which satisfy condition of equivalent availabilities for compared cases.

Two WDM point-to-point systems considered both carry the same amount of capacity: 16×2.5 Gbit/s (Figure 4.9, n_{ch}=16, further Case 1, where n_{ch} is number of wavelength channels) and 4×10 Gbit/s (Figure 4.9, n_{ch}=4, further Case 2), that is, total of 40 Gbit/s. Compared systems are composed of optical transmitters and receivers, multiplexers and demultiplexers, Booster Optical Amplifiers (BOA); Optical PreAmplifiers (POA) and Line Optical Amplifiers (LOA). We assume system length of 500 km and 100 km repeater section length (d_{OA}) for compared systems.

Generally, transmitter is composed of two optical components: laser emitter (DFB laser), and external modulator. In addition, laser emitter should contain Peltier device for temperature stabilization. Although there are other ways to implement transmitter, such as integrated emitter and modulator, assumption that compared systems use the same structure of transmitter seems quite realistic. The main difference in transmitters for two systems lies in accompanying electronic devices, nevertheless, one can assume, for the simplicity of comparison, that receivers are the same in terms of availability performance.

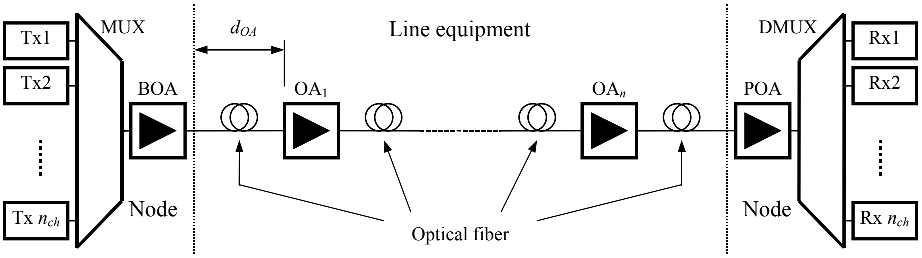


Figure 4.9. – Compared WDM point-to-point systems

Three possible types of multiplexers and demultiplexers could be used, based on either: diffraction gratings, optical filters, or Array Waveguide Gratings (AWG). In addition, some commercially available systems also make use of couplers as multiplexers.

The most important difference between two compared WDM systems lies in the choice of optical amplifiers. All amplifiers are of dual-stage type, with Erbium Doped Fiber Amplifier (EDFA) in each stage, as shown in Figure 4.10.

The booster optical amplifier (Figure 4.10a) is used after the laser emitter to boost the transmitted power to a level required for transmission over fiber, and that is not available from the laser transmitter. Its main characteristic is high output optical power.

At the other end of the communication system, optical preamplifiers (Figure 4.10a) are used to enhance the receiver's sensitivity. Usual characteristics of such amplifiers are high gain, low noise figures and narrow bandwidth.

The line optical amplifier (Figure 4.10a, b, and c) compensates signal power degradation due to attenuation in fiber and fiber connections. It is not obvious when to use dispersion compensation, but under assumption of 500 km system length, we assume that only 10 Gbit/s system needs dispersion compensation. Therefore, amplifier structures presented in Figure 4.10b and Figure 4.10c are possible structures used for 10 Gbit/s system, and represent Cases 2a and 2b respectively, while LOA in Figure 4.10a represent the Case 1. Furthermore, we assume in the model that dispersion compensation element (DCF) is a dispersion-shifted fiber.

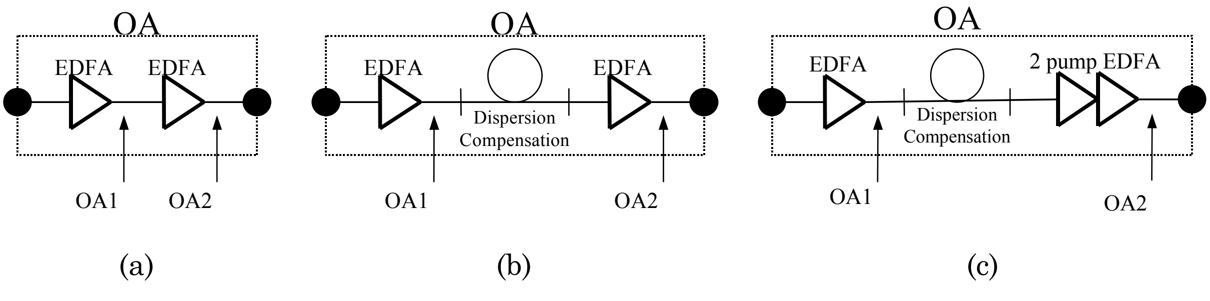


Figure 4.10 – Optical amplifier structures

EDFAs structures are shown in Figure 4.11, a and b. Although there are many other EDFA structures, for example one including Bragg gratings, one should bear in mind that the critical component in EDFA devices is laser pump. Note that two-pump EDFA can be used for second stage in 10 Gbit/s systems in order to compensate relatively high losses in dispersion compensation element. EDFA usual characteristics include input optical signal power between –20 dBm and –5 dBm, flattened gain bandwidth of usually 30 nm wide, and output optical power from 5 dBm to 20 dBm.

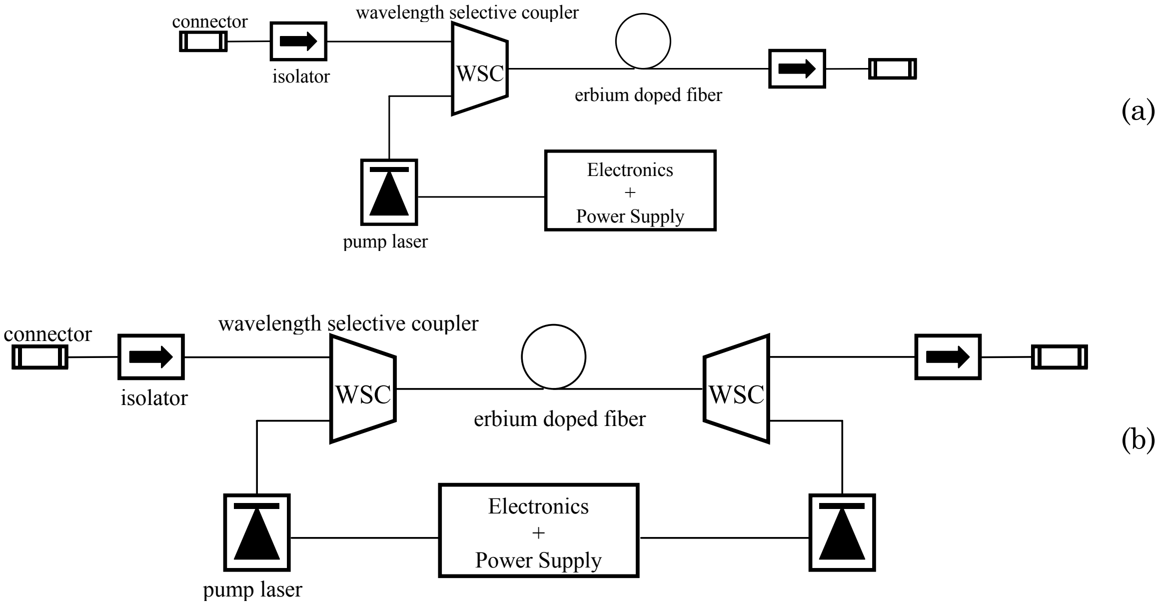


Figure 4.11 – EDFA structure for (a) one pump and (b) two pumps

One of important assumptions made concerns output power levels of EDFA. In order to simplify calculations involved in the comparison, we assume that they are the same for both cases - around 20 dBm. We assume that the difference in the level of output power does not have significant influence on the availability performance of EDFAs. The fact that spectral power for both systems is roughly the same supports this assumption.

Differences between compared cases are listed in the Table 4.1.

Table 4.1. – Compared cases

Case	Number of channels [n_{ch}]	Capacity of a channel [C_{ch}/Gbit/s]	BOA and POA structure [see Figure 4.10]	LOA structure [see Figure 4.10]
1	16	2.5	a	a
2a	4	10	a	b
2b	4	10	a	c

Availability data

Failure and repair rates for optical components (Table 4.2) are taken from the existing data when possible [AV23],[AV24] and [AV25], and for the rest of optical components is estimated through private discussions with experts.

For some critical component/devices availability data is presented as a range of possible values. Failure rates for Erbium doped and dispersion compensation fibers are found to be negligible compared to other component/devices. Thus, the failures in these two components could be ascribed to fusion splice or connector failures. In addition, availability data for electronics are not considered, since it has been integrated within the availability of devices that make use of it.

All optical components, except optical fiber, are assumed to be an indoor components, having same repair times. Note that the same optical fiber (characteristics and length) is used for all compared cases, and it does not influence comparison results.

Table 4.2. – Availability data for optical components

Component/Device		Failure rate [fit[1]]	Component/Device		Failure rate [fit[1]]
Laser pump	pump	100-400	Erbium doped fiber	EDF	negligible
Laser emitter	LE	100-400	Isolator	IS	100
External modulator	EM	2000-5000	Connector	CONN	50-100
Integrated laser modulator	ILM	1000-2000	Fusion splice	FS	50
Optical receiver	Rx	100-400	Optical fiber (per km)	OF	100
Multiplexer (4λ/16λ)	MUX	100/400	Optical switch	X	1000
Demultiplexer (4λ/16λ)	DMUX	100/400	Coupler	CPLR	50
Wavelength selective coupler	WSC	100-200	Dispersion compensation fiber	DC	Negligible

1) 1 fit = 10^{-9} failures per hour or 1 failure per 10^9 hours

EDFAs failure rates depend on the level of optical output power. Even though with the same structure, BOA and POA may not have the same failure rate. For the sake of the simplicity, and without loosing on the credibility of results, one can assume that levels of output power are the same (about 20 dBm). In addition; we also assume equal output power for the EDFAs in LOAs. As a consequence, laser pumps for all cases have equal failure rates.

As stated in previous chapter, our systems use EDFA with one or two pumps. Availability of EDFA is calculated,

$$A_{EDFA1} = A_{CONN}^2 \cdot A_{FS}^6 \cdot A_{IS}^2 \cdot A_{WSC} \cdot A_{EDF} \cdot A_{pump}, \tag{4.35}$$

and since U<<1 we can use the following simplification,

$$1 - U = (1 - U_1) \cdot (1 - U_2) = 1 - U_1 - U_2 - U_1 \cdot U_2 \approx 1 - U_1 - U_2, \tag{4.36}$$

we have

$$U_{EDFA1} \approx 2 \cdot U_{CONN} + 6 \cdot U_{FS} + 2 \cdot U_{IS} + U_{WSC} + U_{EDF} + U_{pump}, \tag{4.37}$$

$$U_{EDFA2} \approx U_{EDFA1} + 2 \cdot U_{FS} + U_{WSC} + U_{pump}. \tag{4.38}$$

Since the structures of BOA and POA are identical for all cases, and output optical powers are also assumed to be equal (see chapter 1), following expressions define unavailability for those components,

$$U_{BOA} = U_{POA} \approx 2 \cdot U_{EDFA1}. \tag{4.39}$$

Using these expressions, we can write unavailability expressions for the optical amplifiers,

$$U_{OA1} \approx 2 \cdot U_{EDFA1}, \tag{4.40}$$

$$U_{OA2a} \approx 2 \cdot U_{EDFA1} + U_{DC}, \tag{4.41}$$

$$U_{OA2b} \approx U_{EDFA1} + U_{DC} + U_{EDFA2}. \tag{4.42}$$

Transmitter is assumed to be composed of two devices: laser emitter and external modulator. Thus we have,

$$U_{Tx} \approx U_{LE} + U_{EM} \tag{4.43}$$

Availability of total capacity

The availability of total capacity is defined as the probability that total amount of the capacity is operational at the given time. Such requirement is fulfilled only if all components of the system work correctly. Having that in mind, one can write unavailability expressions for the two cases (Case 1 and Case 2),

$$U_1 \approx U_{BOA} + U_{POA} + U_{MUX} + U_{DMUX} + U_F + n \cdot U_{OA} + 16 \cdot U_{Tx} + 16 \cdot U_{Rx} \tag{4.44}$$

$$U_2 \approx U_{BOA'} + U_{POA'} + U_{MUX'} + U_{DMUX'} + U_{F'} + n \cdot U_{OA'} + 4 \cdot U_{Tx'} + 4 \cdot U_{Rx'}, \tag{4.45}$$

where *n* is the number of LOAs on the link.

With the assumptions introduced in the first chapter, we have $A_{BOA} = A_{BOA'}$, $A_{POA} = A_{POA'}$, $A_{MUX} = A_{MUX'}$, $A_{DMUX} = A_{DMUX'}$, $A_{Tx} = A_{Tx'}$ and $A_{Rx} = A_{Rx'}$.

As already said in the introduction, the cases are compared by equalizing their availability expression, and drawing a curve of transmitter availability versus laser pump availability. Thus, for $A_1 = A_2$ we have,

$$U_{Tx} = \frac{n}{12} \cdot \left(U_{OA'} - U_{OA}\right) - U_{Rx}. \tag{4.46}$$

The above expression simply shows that two transmission systems have equal availabilities only if loss of availability introduced by a higher number of transmitters and receivers in the Case 1 is compensated by the loss of availability introduced by the slightly complicated amplifying systems in the Case 2a and Case 2b. In all other cases 10 Gbit/s systems perform better, since there are fewer elements that could fail. As stated, this difference is either in dispersion compensation element, or dispersion compensation element and additional laser pump per each optical amplifier. Thus, for the Case 1 and Case 2a we have,

$$U_{Tx} = \frac{n}{12} \cdot U_{DC} - U_{Rx}, \tag{4.47}$$

and since MTTRs for all components are assumed equal, we can write

$$\lambda_{Tx} = \frac{n}{12} \cdot \lambda_{DC} - \lambda_{Rx}, \tag{4.48}$$

since only difference in optical amplifiers for two cases is in additional dispersion compensation element. Results shown in Figure 4.12, say that Case 2a is better than Case 1 for any practically possible value of λ_{pump}, simply because it uses fewer transmitters and receivers, and the decrease in availability performance can not be compensated by the dispersion compensation element, since it could be assumed ideal in terms of failure rates compared to other optical devices.

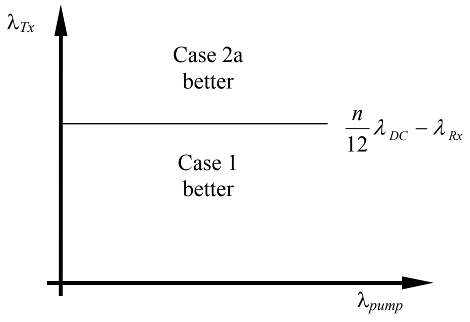


Figure 4.12 – Case 1 vs. Case 2a

The comparison of Case 1 with Case 2b yields following results, which are graphically shown in Figure 4.13:

$$U_{Tx} = \frac{n}{12} \cdot \left(2 \cdot U_{FS} + U_{WSC} + U_{DC} + U_{pump}\right) - U_{Rx}, \tag{4.49}$$

$$\lambda_{Tx} = \frac{n}{12} \cdot \left(2 \cdot \lambda_{FS} + \lambda_{WSC} + \lambda_{DC} + \lambda_{pump}\right) - \lambda_{Rx} \tag{4.50}$$

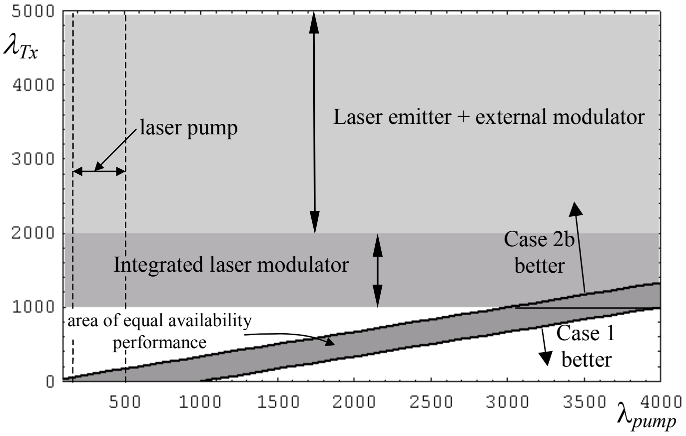


Figure 4.13 – Case 1 vs. Case 2b

Transmitter failure rate intensity as a function of laser pump failure intensity for the case of equal availability performance of compared systems is depicted in Figure 4.13 (area of equal availability performance). On the same picture the possible range of current availability performances for critical components is outlined; for laser pump and two possible transmitter structures, integrated laser modulator or laser emitter + external modulator.

As shown in the Figure 4.13, Case 2b is for the present state of high speed optical technology better than case 1, since the intersection of ranges for transmitters and laser pump drops into the area above equal availability performance. On the other hand, one should be aware of the assumptions which led to such result. Perhaps the biggest consequence arrives from the assumption that in terms of availability performances of multiplexers for both cases are the same. This is perhaps true for the diffraction grating and array waveguide grating based multiplexer technology, but to some limited extent. One must have in mind that nowadays most frequently used technology is filter based, in which availability strongly depends upon the size of multiplexers. On the other hand, the most probable future technology will be AWG, and that gives some weight to our assumptions. At this point it is not clear how bit rate influences on availability of transmitter and receiver. At the end, perhaps most benign assumptions concerns booster optical amplifier and optical preamplifier, since they are not critical, especially for long-haul WDM communication systems.

4.4.1.2. WDM Transmission Link with 1:*N* Shared Protection

Previous section pointed out relatively poor availability performance of today's commercially available transmitters. In order to enhance the availability performance of a transmission system, we introduce the redundancy of critical component, the optical transmitters, as shown in Figure 4.14. The proposed scheme is 1:N protection of transmitters, since N transmitters share same replacement in case of their failure. This scheme is implemented by the use of optical switches on both transmitting and receiving side of a transmission system.

In order to simplify obtained expressions, throughout the chapter following notations are used;

$$U_{TR} = U_{Tx} + U_{Rx}, \tag{4.51}$$

$$U_{TRR} = U_{Tr} + U_{Rr}\,, \tag{4.52}$$

where,

$$U_{Tr} = U_{CPLR} + U_X + U_{TxR}\,, \tag{4.53}$$

$$U_{Rr} = U_{RxR} + U_X + U_{CPLR}\,, \tag{4.54}$$

$$U_{TL} = U_{MUX} + U_{BOA} + U_{OF} + U_{OA}^{n} + U_{POA} + U_{DMUX}\,. \tag{4.55}$$

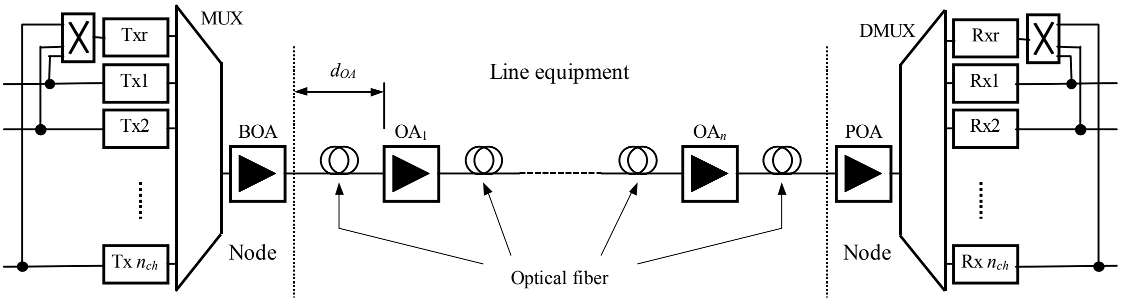


Figure 4.14 – 1:N protection of transmitters

Availability of total capacity

Since we have total of n_{ch}+1 installed channels, including spare one, total capacity is available if any combination of n_{ch} out of (n_{ch}+1) channels is available. Thus, we have

$$U \approx n_{ch}\;U_{TR}\;\left[(n_{ch}-1)\;U_{TR} + U_{TRR}\right] + U_{TL} \tag{4.56}$$

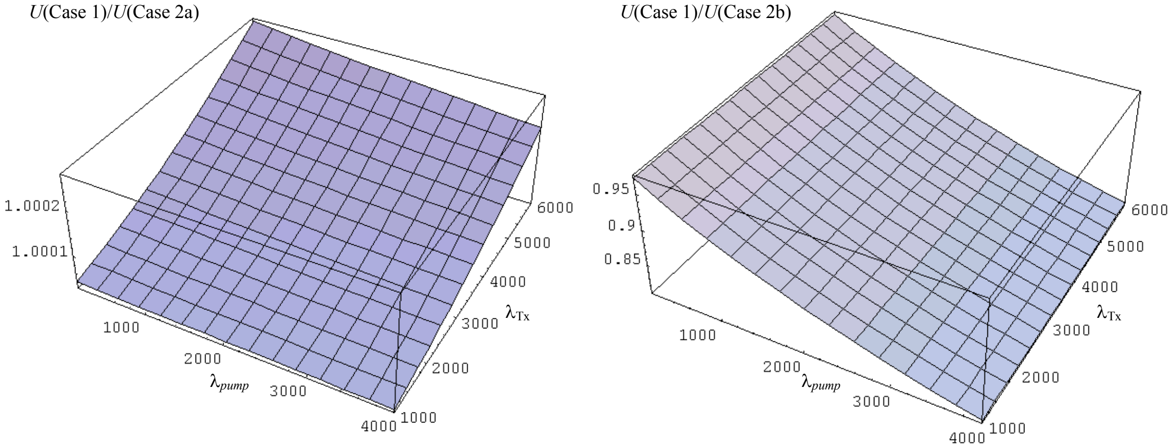


Figure 4.15 – Unavailability of total capacity for 1:*N* WDM transmission link

Figure 4.15 presents comparison of unavailability results for WDM transmission system with 1:*N* protection of transmitters. Results are presented in the form of unavailability value ratios. There are two clear conclusions that arise from the Figure 4.15. First is that Case 2a shows better availabilty performance that Case 1. This is easily explainable by the fact that in Case 2a one has higher degree of redundancy, since number of channels is lower, while the quantity and performance of rest of components is neglectedly different. The second conclusion concerns the graph on the right of the Figure 4.15, which is interpreted in a way that Case 2b has higher unavailability performance than Case 1, and thus, Case 1 is better in terms of availability. This could be perhaps explained by the high influence of the additional pump in LOAs.

Final conclusion could state that the improvement in the transmitter availability performance emphasized the criticality of laser pump.

4.4.1.3. WDM Transmission Systems Comparison: A Conclusion

Comparison of described cases shows that depending on the application of WDM point-to-point transmission systems, in context of availability performance one of the presented solutions should be preferred, being aware of assumptions which led to results. In the case where all of the capacity is required in order to have communication protocols in upper layers functional, a solution with lower number of wavelength channels should be used. This could be explained by the lack of redundancy of any type in such systems. Consequently, it is more probable for the non-redundant system with less number of components to be non-faulty. One way to introduce redundancy is through the use of optical protection of transmitters, which is justified by the fact that transmitter availability is very critical point considering actual data ($\lambda_{Tx} >> \lambda_{OA}$). A possible implementation of optical transmitter protection is through 1:*N* protection of transmitters and receivers. As the results for the 1:*N* protection of transmitters showed, the improvement of transmitter availability performance emphasized criticality of another optical component, laser pump.

On the other hand, when higher layer protocols require as much as possible amount of capacity, one should prefer the case with higher number of wavelength channels (lower channel capacity). This is due to fact that failure of a component which is responsible for lower amount of capacity, causes less damage to the overall capacity. Note that in this case specific kind of redundancy is used – the system will work even with failures, but with a lower amount of available capacity. In addition, if the additional redundancy is added to a system, results point out that laser pump component is even more critical.

4.4.1.4. Mesh Networks

The availability model for mesh networks, as described here, was introduced in [AV15]. It was further enhanced in [AV01], and [AV28]. In addition, its application to the availability analysis has been presented in [AV26] and [AV27]. This availability model is the most general one, and can be, with few modifications, applied to different P&R and topological paradigms. The model is based on the logical expressions defining the non-faulty state of transport entities.

The first transport entity, starting from the bottom, is wavelength channel (λ). Wavelength channel corresponds to a single wavelength on any fiber in the network. A wavelength channel is available only if corresponding fiber, optical line amplifiers, booster optical amplifiers, optical pre-amplifiers, multiplexers and de-multiplexers are available. Thus, we can write following logical expression,

$$\begin{aligned} LE(\lambda_{jkl}) = {} & E_{mux}(\upsilon_1, j, k) \cap E_{dmux}(\upsilon_2, j, k) \cap E_{boa}(\upsilon_1, j, k) \cap \\ & E_{poa}(\upsilon_2, j, k) \cap \left(\bigcap_{\forall loa \in (j,k)} E_{loa}(j,k) \right) \cap E_{fiber}(\phi_{jk}) \end{aligned}, \tag{4.57}$$

where j denotes link e_j, k fiber ϕ_{jk}, and l wavelength on the fiber ϕ_{jk}. The letter E generically denotes network element, with index denoting type of element. In a WDM network a fiber is terminated by the multiplexer at the transmitting side and DMUX at the receiving side. In the expression above, node υ_1 is at the transmitting side, while node υ_2 is at the receiving side, hence link e_j connect these two nodes in direction from node υ_1 to node υ_2. In most of the cases, however, failure of the fiber is caused by the cut of the corresponding cable which affects all fibers within the cable. Since the dependence between the failure of the cable and fiber is 100%, we can modify expression as follows,

$$LE(\lambda_{jkl}) = E_{mux}(v_1, j, k) \cap E_{dmux}(v_2, j, k) \cap E_{boa}(v_1, j, k) \cap \\ E_{poa}(v_2, j, k) \cap \left(\bigcap_{\forall loa \in (j,k)} E_{loa}(j,k) \right) \cap E_{OCable}(e_j) , \tag{4.58}$$

where $E_{OCable}(e_j)$ denotes optical cable on link e_j. We assume that each link contains exactly one optical cable.

Next transport entity is the lightpath (Λ). Let us assume that the lightpath is routed over path π, a simple sequence of nodes and links, between source (v_s) and destination node (v_d). A lightpath could be then viewed as the concatenation of wavelength channels on a given path. A logical expression is as follows,

$$LE(\Lambda_{sd}, \pi_{sd}) = \left(\bigcap_{\forall e_j \in \pi_{sd}} LE\left(\lambda_{jkl}\right) \right) \cap \\ \left(\bigcap_{\forall v_i \in \pi_{sd}} E_x(v_i, \lambda_{j_{-1}kl}) \cap E_x(v_i, \lambda_{j_{+1}kl}) \cap E_{wc}(\phi_{j_{+1}k}, \lambda_{j_{+1}kl}) \right) \cap . \\ E_{xedge}(v_s) \cap E_{tp}(v_s) \cap E_{xedge}(v_d) \cap E_{tp}(v_d) \tag{4.59}$$

In the expression above j_{-1} denotes link previous to node v_i, and j_{+1} link that follows node v_i in a path π.

In its simplest case, for the no protection case, logical channel is composed of only two lightpaths, one per each direction. Thus, we can write,

$$LE(LCh_{sd}) = LE(\Lambda_{sd}, \pi_{sd}) \cap LE(\Lambda_{ds}, \pi_{ds}) . \tag{4.60}$$

Quite generally, it is possible to have different paths for two directions, but this leads to certain problems, such as different propagation delays. In addition, if different paths are assumed for two directions, more components will be used, and bearing in mind logical AND relationship between two directions, this will lead to lower availability values. This is the reason why we consider only symmetrical routing in this thesis; π_{ds} contains same elements as π_{sd}, the only difference being in reverse sequence.

For the 1+1 protection, each direction uses two lightpaths, routed over two independent paths (node or link), primary (π_{psd}) and backup (π_{bsd}). Hence,

$$LE(LCh_{sd}) = \left(LE(\Lambda_{sd}, \pi_{psd}) \cup LE(\Lambda_{sd}, \pi_{bsd})\right) \cap \\ \left(LE(\Lambda_{ds}, \pi_{pds}) \cup LE(\Lambda_{ds}, \pi_{bds})\right) , \tag{4.61}$$

A logical channel will be available if for each direction at least one lightpath is available.

In 1:1 (Path) protection, resources, e.g. wavelength channels, can be shared by a number of backup lightpaths. For example, consider a scenario from the Figure 4.16. Figure shows two pairs of primary and backup lightpaths. Failure on any of the resources that P_1 uses will activate B_1. The same holds for the P_2 and B_2 pair.

In the scenario two backup lightpaths B_1 and B_2 share the resources on link *C-D*. If we design the network (routing and wavelength assignment) with the assumption that primary lightpaths do not share resources, i.e.

$$P_1 \cap P_2 = 0 ,$$

the result will be survivability of a network for any single failure in a network. For any pair of the primary and backup lightpath following should be also valid,

$P_1 \cap B_1 = 0$,

$P_2 \cap B_2 = 0$.

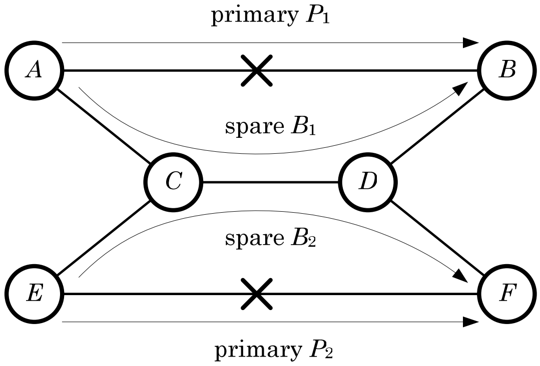


Figure 4.16. – An example of resource sharing

The shared backup lightpath set (*SBLS*) of a primary lightpath P_i is defined so that it contains primary paths P_x with the following properties,

$$SBLS(P_i) = \{P_x : B_i \cap B_x \neq 0\}.$$

SBLS contains primary lightpaths whose backup lightpaths share resources with the backup lightpath of the P_i. In other words, the protection of P_i can not be activated in parallel with protection activation of a $SBLS(P_i)$ member.

Logical expression for a logical channel in 1:1 protection regime is written as,

$$\begin{aligned} LE(LCh_{sd(1:1)}) = {} & \left\{ LE(\Lambda_{sd}, \pi_{psd}) \cup \left[LE(\Lambda_{sd}, \pi_{bsd}) \cap \bigcap_{\substack{\forall LE(\Lambda_{ab},\pi_{pab}) \\ \in \\ SBSL(LE(\Lambda_{sd},\pi_{psd}))}} LE(\Lambda_{ab}, \pi_{pab}) \right] \right\} \cap \\ & \left\{ LE(\Lambda_{ds}, \pi_{pds}) \cup \left[LE(\Lambda_{ds}, \pi_{bds}) \cap \bigcap_{\substack{\forall LE(\Lambda_{ab},\pi_{pba}) \\ \in \\ SBSL(LE(\Lambda_{ds},\pi_{pds}))}} LE(\Lambda_{ba}, \pi_{pba}) \right] \right\} \end{aligned} . \qquad (4.62)$$

The logical channel will be non-faulty if for both directions either primary lightpath is active, or protection lightpath can be activated. Protection lightpath can be activated if its elements are in non-faulty state, and all of the members of a corresponding SBSL are in non-faulty state.

In cases where multiple spare lightpaths exist, for example in cases of SPAF and span protection, we can generalize expressions,

$$\begin{aligned} LE(LCh_{sd}) = {} & \left(LE(\Lambda_{sd}, \pi_{psd}) \cup \left(\bigcup_{\forall \Lambda_{sd} \in LCh_{sd}} LE(\Lambda_{sd}, \pi_{bsd}) \cap \left[\bigcap_{\substack{\forall LE(\Lambda_{ab},\pi_{pab}) \\ \in \\ SBSL(LE(\Lambda_{sd},\pi_{psd}))}} LE(\Lambda_{ab}, \pi_{pab}) \right] \right) \right) \cap \\ & \left(LE(\Lambda_{ds}, \pi_{pds}) \cup \left(\bigcup_{\forall \Lambda_{ds} \in LCh_{sd}} LE(\Lambda_{ds}, \pi_{bds}) \cap \left[\bigcap_{\substack{\forall LE(\Lambda_{ba},\pi_{pba}) \\ \in \\ SBSL(LE(\Lambda_{ds},\pi_{pds}))}} LE(\Lambda_{ba}, \pi_{pba}) \right] \right) \right) \end{aligned} , \qquad (4.63)$$

Finally, connection is composed of several channels. The number of channels depends on the capacity of each channel (full wavelength capacity, *C*), and capacity of logical connection. In order for a connection to be available, all of the channels should be available,

$$LC_{sd} = \bigcap_{\forall LCh_{sd} \in LC_{sd}} LCh_{sd} \,. \tag{4.64}$$

4.4.1.5. P-cycle Networks

Availability models used for mesh based networks can be easily applied to p-cycle based networks. This is due to the fact that p-cycle based networks can be seen as that of span protection on the level of wavelength channel. We start the discussion with definitions of terms that will be used to define generic availability model for a p-cycle based networks.

Notion of the term lightcycle has been introduced in the Chapter 2. We assume in the thesis that a lightcycle Θ_a protects wavelength channels λ_{jkl} that can be on the same cycle as lightcycle, or straddling to the cycle. For each lightcycle Θ_a we define lightcycle protection coverage set (*PPCS*), which defines wavelength channels that can be protected by lightcycle. The $PPCS(\Theta_a)$ is further divided into on-cycle $PPCS_{oc}(\Theta_a)$ and straddling $PPCS_{st}(\Theta_a)$ subset,

$$PPCS(\Theta_a) = PPCS_{st}(\Theta_a) \cup PPCS_{oc}(\Theta_a) \,. \tag{4.65}$$

If lightcycle Θ_a is placed on a cycle χ_a, $PPCS_{oc}(\Theta_a)$ can be defined as follows,

$$PPCS_{oc}(\Theta_a) = \left\{ \lambda_{jkl} : e_j \in \chi_a \right\}.$$

$PPCS_{st}(\Theta_a)$ can be defined as,

$$PPCS_{st}(\Theta_a) = \left\{ \lambda_{jkl} : e_j \notin \chi_a, e_j = \left(v_x, v_y\right) \in \chi_a \right\}.$$

Now we define a part of the p-cycle that protects wavelength channel λ_{jkl}. This is actually a lightpath,

$$\Lambda_{\Theta_a jkl} \subseteq \Theta_a \,.$$

Finally, for a lightcycle Θ_a, and wavelength channel λ_{jkl}, we define a shared protection coverage set (*SPPCS*). The set is a subset of the corresponding *PPCS*, that defines wavelength channels λ_{fgh} that can be simultaneously protected with the λ_{jkl} by Θ_a,

$$SPPCS(\Theta_a, \lambda_{jkl}) \subseteq PPCS(\Theta_a) \,.$$

This will be the case, for example, for straddling wavelength channels.

Logical expression defining non-faulty state of the single direction part of a logical channel can be written as,

$$LE(LCh'_{sd}) = \bigcap_{\forall \lambda_{jkl} \in \Lambda_{sd}} \left\{ \lambda_{jkl} \cup \left[\Lambda_{\Theta_a jkl} \cap \bigcap_{\lambda_{xyz} \in PPCS(\Theta_a) \setminus SPPCS(\Theta_a, \lambda_{jkl})} \lambda_{xyz} \right] \right\}.$$

In the expression, Λ_{sd} is the working lightpath in a direction from node *s* to node *d*. The expression says that each wavelength channel λ_{jkl}, a part of a working lightpath Λ_{sd}, is protected by the lightpath $\Lambda_{\Theta_a jkl}$, which is a part of a lightcycle Θ_a. The protection lightpath $\Lambda_{\Theta_a jkl}$ will be at disposal for protecting λ_{jkl} only if wavelength channels that are part of the $PPCS(\Theta_a)\setminus SPPCS(\Theta_a,\lambda_{jkl})$ are in non-faulty state. Otherwise, the $\Lambda_{\Theta_a jkl}$ will be used for protection purposes by some other wavelength channel.

4.4.2. Optical Packet Switching

In the section, generic availability model, based on the one developed for circuit switched networks, is presented. The availability model for OPS networks, as described here, has been introduced in [PS05]. In addition to WDMPoP nodes, IPPoP nodes are introduced, as described in [AV32], in order to serve as a source and destination for packet traffic.

4.4.2.1. Transport Entity Architecture

Transport entities form a logical hierarchy describing network communication on all levels, starting from the bottom at wavelength channel, and ending with a complete end-to-end communication across the network. A bi-directional relationship between physical elements and traffic that they serve enables model structuring after constructing transport entities, as well as traffic adjustments after the network has been dimensioned and evaluated.

Traffic demands are logically the highest level of the hierarchy as they describe a unidirectional end-to-end communication between two IPPoP nodes. All demands are determined by an IPPoP node pair and amount of traffic between them (Figure 4.17).

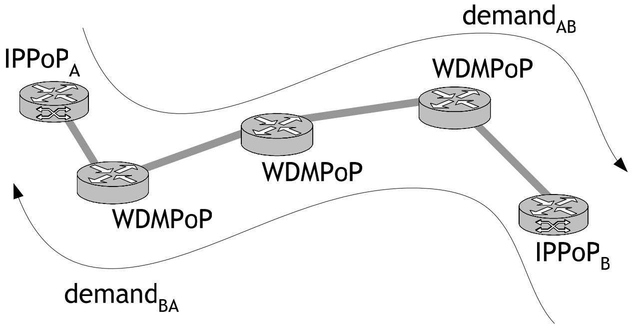


Figure 4.17. – Network demands

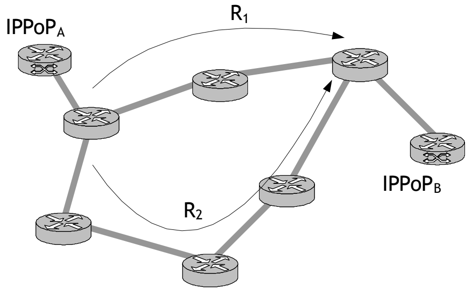


Figure 4.18. – Routes of one demand

A demand can make use of several different physical paths, implying that a communication between the same node pair utilizes different nodes and links. Such division is necessary due to possible physical limitations of nodes or intended different communication properties for certain parts of traffic (QoS support by shorter or more reliable connections). Different paths used by the same demand are described using routes. Figure 4.18 depicts a demand between nodes A and B which uses routes R_1 and R_2.

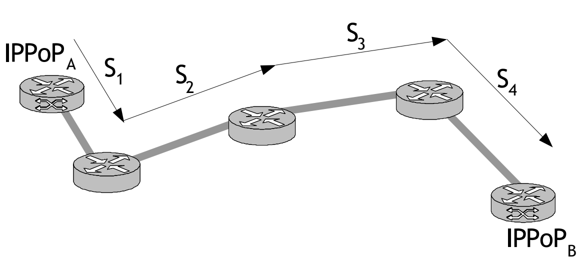


Figure 4.19. – Sections of one route

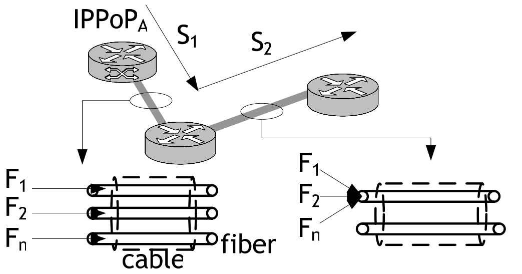


Figure 4.20. – Flows of one section

Each route is divided into sections defined by a pair of directly connected (adjacent) nodes. Route R_1 from the previous example has two access sections S_1 and S_4 (an access section is defined by the IPPoP-WDMPoP pair), and two core sections S_2 i S_3 (a core section is defined by the WDMPoP-WDMPoP pair) as shown in Figure 4.19. Apart from the node pair, sections are also determined by the direction, implying that demands in opposite directions can use different sections between each node pair.

One or more flows correspond to each section. Flows define a portion of demand data capacity transported using one fiber. The assumption is the full wavelength conversion usage which enables all flows on one fiber (link) to access all the fiber channels. Flows belonging to access sections (e.g. S_1 i S_4) use fibers with Sonet/SDH framed baseband transmission, suggesting single flow per fiber, while core flows can utilize WDM transmission, indicating one or more flows per fiber (Figure 4.20).

Quite generally, different number of flows could correspond to a single demand on different sections. The number of flows is determined by the section properties (including channel capacity and the number of wavelengths), and the number of demands in the same direction that use the physical connection between the pair of nodes defining the section. Figure 4.21 depicts a constructed situation where the communication between node pair defining section S_2 belonging to demand D_{AB} on route R_1 is being traversed by the set of other demands denoted as $\{D\}_2$. The next number of flows in the next section S_3 is determined by the next set of demands $\{D\}_3$ which, generally speaking, differs from the set $\{D\}_2$. Notice that demand sets $\{D\}_2$ and $\{D\}_3$ do not utilize the same sections as each demand has its own sections on each pair of nodes it traverses.

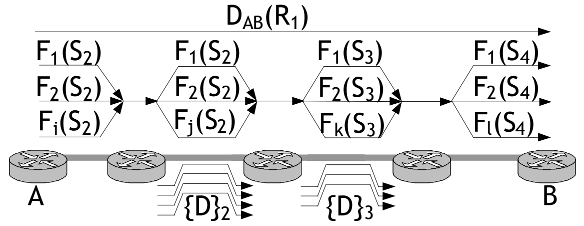


Figure 4.21. – Demand flows on one route

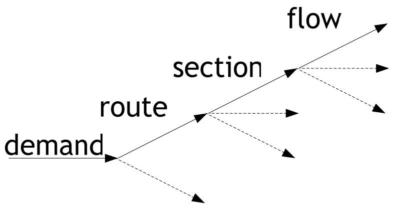


Figure 4.22. – Transport entity hierarchy

Figure 4.22 summarizes a transport entity logical hierarchy. It is a tree like structure with the fiber granularity in the case of full wavelength conversion, or wavelength channel in case of network with wavelength conversion.

4.4.2.2. Availability structure

The calculation of transport entity availability is based on logical expressions defining a transport entity by using (enumerating) physical components they use.

The availability of a flow depends on the availability of equipment it uses. This equipment set includes multiplexer/demultiplexer, space switch, wavelength converters, amplifiers and transponders in the case of the access flow (Figure 4.23).

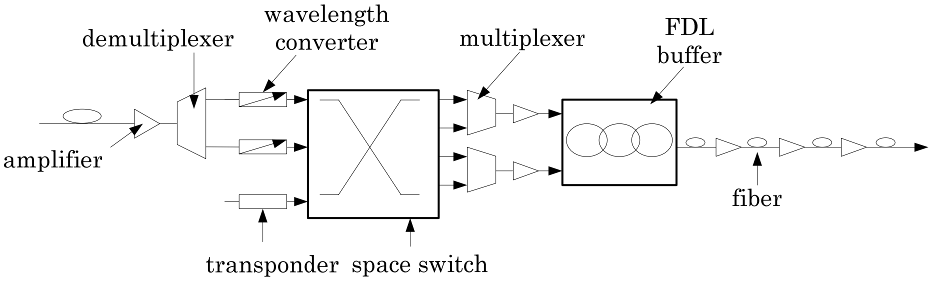


Figure 4.23. – Equipment defining a flow

The problem of definition of the set of equipment defining a flow is solved by differentiating access and core flow (Figure 4.24). Access flow is defined by the equipment set that includes all equipment used till signal multiplexing in the next core node. The corresponding equipment set in the egress access flow is void if we neglect the probability of cutting the access cable. In this work this probability is finite (although low).

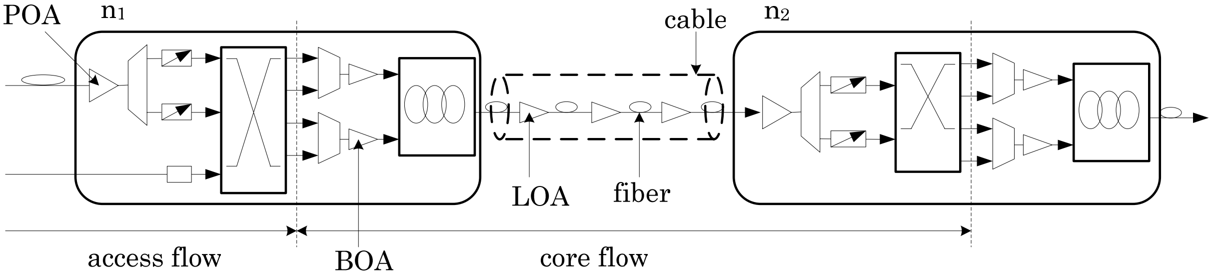


Figure 4.24. – Equipment defining access and core flow

Using the previous picture we can easily deduct a logical expression defining used equipment,

$$\begin{aligned} F_{core}(c,f) = E_{mux}(n_1,c,f) \cap E_{boa}(n_1,c,f) \cap \left(\bigcap_{\forall LOA \in (c_2,f_2)} E_{loa}(c,f) \right) \cap f(c) \cap \\ \cap E_{dmux}(n_2,c,f) \cap \left(\bigcap_{\forall Wc \in (C,f)} E_{wc}(n_1,c,f) \right) \cap E_{sw}(n_2) \end{aligned}, \tag{4.66}$$

where c denotes a cable connecting nodes n_1 and n_2, and f the fiber in the cable. The letter E generally denotes a network element, while the subscript denotes the element type. The expression above describes a core flow belonging to one demand on one fiber between a node pair. The same expression for the core flow equals to,

$$F_{in}(c,f) = E_{trans}(n_s,c,f) \cap E_{sw}(n_s), \tag{4.67}$$

where c denotes access cable of the source node n_s, and f the fiber with the baseband transmission in this cable.

In the expression above one can incorporate an additional logical entity describing a fiber failure caused by cable cut. The full dependence between the cable cut and a fiber failure is assumed, yielding

$$\begin{aligned} F_{core}(c,f) = E_{mux}(n_1,c,f) \cap E_{boa}(n_1,c,f) \cap \left(\bigcap_{\forall LOA \in (c_2,f_2)} E_{loa}(c,f) \right) \cap f(c) \cap \\ \cap E_{dmux}(n_2,c,f) \cap \left(\bigcap_{\forall Wc \in (C,f)} E_{wc}(n_1,c,f) \right) \cap E_{sw}(n_2) \cap OC(f) \end{aligned}, \tag{4.68}$$

where $OC(f)$ denotes the optical cable holding the fiber i. For the ingress access flow it can be written,

$$F_{in}(c,f) = E_{trans}(n_s,c,f) \cap E_{sw}(n_s) \cap OC(f). \tag{4.69}$$

The next higher transport entity is section which comprises all flows between two nodes belonging to the same demand,

$$S_{core}(c) = \bigcap_{\forall f \in c(n_1,n_2) | F_{core} \in S_{core}} F_{core}(c,f). \tag{4.70}$$

One has to bear in mind that upper union counts only flow belonging to the same demand. The same expression for the access section equals,

$$S_{in}(c) = \bigcap_{\forall f \in c(n_s) | F_{in} \in S_{in}} F_{in}(c,f), \tag{4.71}$$

where is the access cable of the source node n_s analyzed.

Each flow is additionally determined by its wavelength in the case of no wavelength conversion,

$$S_{core}(c) = \bigcap_{\forall f \in c(n_1,n_2) | F_{core} \in S_{core}} F_{core}(c,f,\lambda(f)). \tag{4.72}$$

The wavelengths of the access flows are generally not determined as they depend on the optical interface of the line cards in IPPoP nodes.

A route is lowest transport entity describing communication between the end nodes. The physical path used for communication between the source (n_s) and the destination (n_d) can be represented as an array of nodes and cables/fibers using a path π,

$$R(n_s,n_d,\pi) = \left(\bigcap_{S_{in} \in R(n_s,n_d,\pi)} S_{in}\left(c\left(n_s\right)\right) \right) \cap \left(\bigcap_{S_{core} \in R(n_s,n_d,\pi)} S_{core}\left(c\right) \right), \tag{4.73}$$

where π denotes an array of nodes and cables corresponding to the selected physical path.

A deflection route has to be taken into account in the case of deflection routing what the expression of the core section changes to

$$S_{core}(c) = \left(\bigcap_{\forall f \in c(n_1,n_2) | F_{core} \in S_{core}} F_{core}\left(c,f,\lambda\left(f\right)\right) \right) \cap R_{DR}\left(S_{core},\pi_{DR}\right), \tag{4.74}$$

where R_{DR} denotes a deflection route corresponding to the selected section. This route uses a physical path π_{DR}. The access section expression remains unchanged as access is not protected.

A demand is generally defined as a complete unidirectional communication between the end nodes n_s and n_d:

$$D(n_s,n_d) = \bigcap_{\forall R(n_s,n_d,\pi) \in D(n_s,n_d)} R(n_s,n_d,\pi). \tag{4.75}$$

In the case of OCS and OPS availability comparison, the upper logical expression has to be extended to include bidirectional communication, as in the case of the bidirectional logical connection in the OCS network:

$$D'(n_s,n_d) = D(n_s,n_d) \cap D(n_d,n_s). \tag{4.76}$$

The use of such definition will be emphasized in the availability analysis.

4.5. Overview of the Related Work

There is limited number of references dealing with the availability and/or reliability modeling of an optical transport network, or optical transport systems in general.

In [AV33][AV34] a reliability model developed for SDH/SONET ring networks [AV34] have been applied to WDM self-healing networks. However, although the model addresses level of a physical component, it can be applied to ring networks of limited size, and not to interconnected optical ring networks. Only availability of a lightpath is calculated. On the similar fundaments, the same author in [AV35] presents an availability model for the SRP [AV37] rings.

In a number of references, a few of them being [AV38][AV04], availability models are simplified in the manner that only high level of detail is considered, i.e. level of links and nodes are treated as availability entities. Such simplification can not take into account complex dependencies between physical components.

Availability models presented in the chapter are original in sense that they can be applied to an arbitrary level of network detail. They are defined in a manner so that they can be analyzed by the procedures also presented or listed in the chapter. The models can take into account, depending on the considered level of detail, complex dependencies between components of a network. Such fine level of detail, on the one side requires complex procedures during the analysis process, but on the other hand provides more accurate results that can be furthermore used in the creation of simplified availability models. Such simplified availability models can be consequently used in the optimization procedures.

The availability models and procedures presented in the chapter are part of the integrated framework for network availability analysis. The result of this is that different analytical and simulation techniques can be applied to the same availability model.

5.

Design Procedures

Previous chapter described generic availability models that can be used to analyze any OTN, and thus MSPN. In order to perform availability analysis of the specific optical transport network as described in previous chapter, the network has to be fully defined in terms of resources (equipment) and interconnections between these resources. The chapter describes procedures used to create completely defined software model of optical transport network on which availability analysis procedures can be performed. Results of the analysis are presented in the next chapter.

The first part of the chapter defines input parameters for the design procedures. This part of the chapter also gives a high level view of the design procedures used in creation of software model of an optical transport network.

All of the procedures and methods are based on generic heuristic search techniques, and due to the fact next part of the chapter gives an overview of general purpose heuristic search techniques. This part presents three such techniques.

The “Nyx” optimization kernel is architectured around similarities between general heuristic search techniques. In the second part of the chapter, architecture of the “Nyx” optimization kernel is presented.

In the final part of the chapter, methods and procedures for creation of fully defined software models of optical transport networks are presented.

5.1. General Description of the Design Process

The aim of the network modeling procedure is to create network structure, including links and nodes, and to form transport entities needed for availability calculation [AV01]. Figure 5.1 [AV28][DE02] depicts availability modeling procedure. The procedure consists of following steps;

- Preprocessing of input data,
- Routing and wavelength assignment,

- Node structuring,
- Transport entity creation, and
- Availability analysis.

Input data contains topology specification (COST 266 topologies) [AV04], and traffic data needed to built the traffic matrix. Topology information contains the list of nodes and links and allows creation of connectivity matrix, and link length matrix.

At this point of the design process, nodes in the topology represent some geographical points characterized by the geographical longitude and latitude. Geographical distance between the nodes is calculated using the Haversine formula [DE08]. Geographical distances are corrected (made longer) in order to represent link lengths [DE09].

Traffic model uses link lengths and traffic data to generate traffic matrix, or traffic for each node pair. The traffic volume is divided by the channel capacity (eg. SDH line capacity) to obtain required number of channels to support each communication. The traffic model serves in this step to generate capacity requirements.

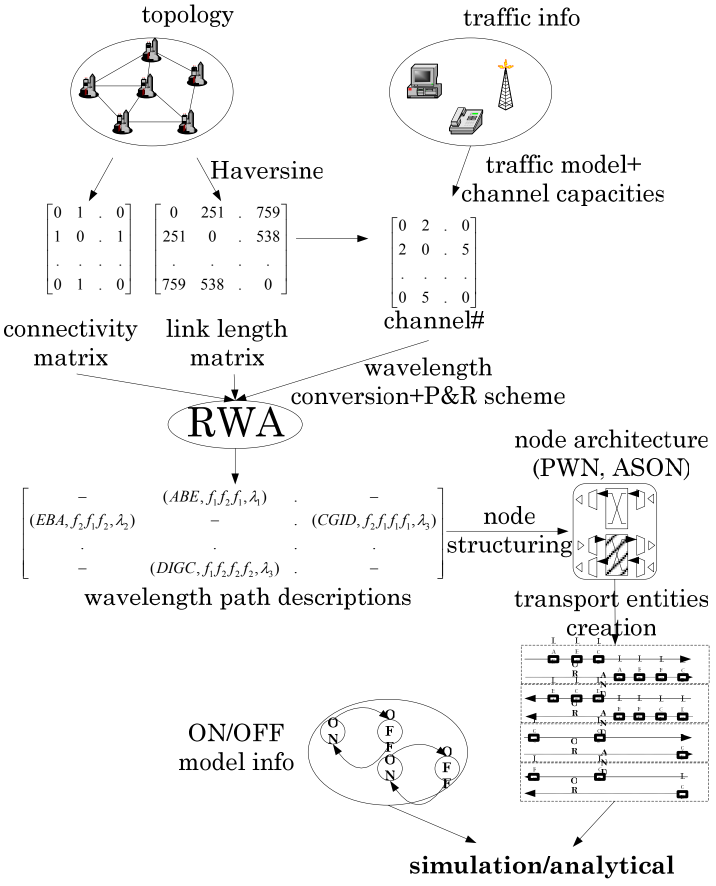


Figure 5.1. – Network modeling procedure

The second step is to determine physical paths used by each communication and to assign wavelengths. Physical path is determined by the sequence of nodes, sequence of fibers and sequence of wavelengths. The process is in the literature known as routing and wavelength assignment (RWA) [DE10][DE12][DE13]. The choice of P&R scheme is included in this step.

Physical paths, fiber information and wavelength vectors suffice for node structuring assuming that the node architecture is determined. Structured nodes and links serve as an input data for creation of transport entities and logical hierarchy.

Availability model parameters (*MTTF* - mean time to failure and *MTTR* - mean time to repair) are used together with the logical hierarchy to determine network availability using simulation or analytical procedure.

In the case of MSPN, due to the fact that full wavelength conversion is possible, wavelength assignment will not occur, since lightpath (or wavelength path) will occupy first free wavelength channel on any of optical links on its path. Thus, RWA problem becomes only routing problem, and in this regard, there are two possible scenarios;

- Shortest Path Routing, and
- Optimized Routing.

In the first case, a transport entity is routed over shortest path. Without protection, logical channel is composed of two lightpaths that are routed over shortest path, but in opposite direction. In order to determine shortest paths the algorithm of Dijkstra is used [GA02].

In the case of 1+1 or 1:1 protection, for each working lightpath, protection (or backup) lightpath is determined. The protection lightpath is routed over path that is link or node independent to the path over which working lightpath is routed. The algorithm of Dijkstra is used in this case too; first in order to determine shortest path, and then to determine shortest link and/or node independent to the shortest path. This is simply achieved by virtual deletion of nodes and links of the shortest path, followed by application of Dijkstra algorithm.

In the case of optimized routing without protection, traffic can be routed over any path between pair of nodes. In the optimization process, for each node pair *k* shortest paths are enumerated using the algorithm of Eppstein [GA05], and for each logical channel a path is selected out of the set of *k* shortest paths, depending on the goal of the optimization (traffic load, minimum blocking etc.).

In the case of optimized routing and 1+1 or 1:1 P&R scheme, *k* shortest independent path pairs are enumerated by using algorithm presented in [GA04]. A pair of independent paths is used to route working and protection lightpaths. Similar to the no protection scenario, in the optimization procedure a pair of independent paths is selected for each logical channel, depending on the optimization goal.

Sets of *k* shortest paths or *k* shortest independent path pairs are optimization variables in possible optimization procedures. Optimal values of optimization variables are created by an optimization procedure. In the thesis we assume application of general heuristic search techniques in finding optimal values of optimization variables.

5.2. General Heuristic Search Techniques

In many cases of telecommunication system design, the problems to be solved are referred to as optimization problems of high complexity in both time and space domain. One way in searching for a (quasi)optimal solution is application of heuristic search methods.

Many heuristic methods have been proposed in the last couple of decades, most of them being tailored to a particular problem, but three among them have become particularly popular recently: genetic algorithm (GA), simulated annealing (SA) and tabu search (TS). All three of them have arisen at least in part from a study of natural processes which perform an analogy of optimization. Their popularity lies mainly in the applicability to the wide variety of problems.

Three modern heuristic search techniques presented in the chapter differ from the traditional methods in the following aspects:

- They work with encoded solutions, not the solutions themselves, and
- They use goal function, not other auxiliary knowledge, such as derivatives.

These two facts make listed techniques applicable to problems for which there is a limited knowledge, i.e. only goal function. This is the reason why we term such techniques general heuristic search techniques (GHST). In the subsequent section GA, SA and TS are briefly explained.

5.2.1. Genetic Algorithms

Genetic algorithms [GH01] are based on analogy with the processes of the natural genetics. The structure of a simple genetic algorithm is shown in Figure 6. Unlike SA and TS, GAs work with population of possible solutions, which are in GA terminology called chromosomes. In addition, the goal function is called fitness function.

```
Genetic Algorithm {
      k = 0;
      Initialize_Population( );
      foreach Chromosome in Population {
            Evaluate_Fitness( Chromosome );
      }
      do {
            k = k + 1;
            Selection( );
            Crossover( );
            Mutation( );
            foreach Chromosome in Population {
                  Evaluate_Fitness( Chromosome );
            }
      } while( stop_criterion_not_reached );
}
```

Figure 5.2. – Genetic Algorithm

In each iteration of the algorithm, population experiences utilization of three main GA operators. During *selection*, best solutions (chromosomes) are selected to be members of a subsequent generation. Depending on a selection type, this is achieved with more or less influence of stochastics.

Crossover implements the exchange of genetic material between two randomly chosen chromosomes. In addition, parts of the solutions to be exchanged are also chosen randomly.

Finally, *mutation* operator is related to a random alteration of gene value, which can be optimization variable, or its part. In this context, the role of mutation is secondary - to recover lost genetic material.

It is often said that GA uses stochastic transition rules - this means that genetic operators, namely crossover and mutation, are applied with probabilities p_c and p_m respectively. Generation gap is referred to as the fraction of a population, in the interval (0,1), which takes part in the reproduction procedure creating a new generation.

In each GA application one should define how to generate the initial population and how to stop the algorithm. The initial population could be generated at random, or as genetic material from a previous procedure. The termination of GA running could be done simply by counting if a prescribed number of steps are reached, or by testing if a termination criterion is fulfilled.

5.2.2. Simulated Annealing

The Simulated annealing algorithm [GH02] makes an analogy between a physical many-particle system and a combinatorial optimization process. The solutions in an optimization problem are equivalent to the energy states of a physical system; the cost of a solution is equivalent to the energy of a state, while the control parameter plays the role of the temperature. The simulated annealing algorithm is simply an iteration of algorithm for simulation of annealing, evaluated at decreasing values of the control parameter.

```
Simulated Annealing {
    Initialization( $i_{start}$, $c_0$, $L_0$ );
    $k = 0$;
    $i = i_{start}$;
    $c_k = c_0$;
    do {
        for $l = 1$ to $L_k$ do {
            Generate( $j$ from $S_i$ );
            if $f(j) \le f(i)$ then
                $i = j$;
            endif
            else if exp[(f(i)-f(j))/c] > random[0,1) then
                $i = j$;
            endif
        }
        $k = k + 1$;
        Calculate_Length( $L_k$ );
        Calculate_Control( $c_k$ );
    } while( stop_criterion_not_reached );
}
```

Figure 5.3. – Simulated Annealing Algorithm

The general structure of a SA algorithm is shown in Figure 5.3. It consists of two loops: in the first a control parameter c_k is decreased according to a following function:

$$c_k = \alpha\ c_{k\text{-}1}\ ,$$

where α is a real constant in the range (0, 1). In an inner loop, in k-th generation, a neighborhood of a current solution is partially examined or, more precisely, L_k solutions within it,

$$L_k = L_{k-1} / \beta^{0.1}\ ,$$

where β is a real constant > 1. The actual number of transitions executed in k-th iteration of algorithm is,

$$L_k' = \min\{L_k, L_{\max}\},$$

where L_{max} is the maximum number of accepted transitions for an iteration of algorithm. The solution is accepted to be a subsequent one if it is better than a current one or with certain probability if it is worse. Thus, SA accepts both improvements as well as deteriorations in goal function. Initially, at large values of control parameter, large deteriorations will be accepted. As control parameter decreases, only smaller deteriorations will be accepted. For generating a solution from a neighborhood of a current one (transition), the 2-change algorithm [GH02] has been used.

5.2.3. Tabu Search

Tabu search [GH03], like simulated annealing, is based on a neighborhood search with local optima avoidance, but in a deterministic way, which tries to model human memory process.

Memory is implemented by the implicit recording of a previously seen solutions (**H**), and neighborhood (**$N(x_{now},H)$**) is modified so that memorized solutions could not be a subject to evaluation, i.e. they are tabu, for a certain number of iterations (*tabu tenure*). For example, if solutions are binary coded (i.e., in Gray code), we can assume that the neighborhood of a current solution is defined with respect to Hamming distance. Structure of tabu search is shown in Figure 5.4.

```
Tabu_Search {
        k = 0;
        Initialize($x_{now}$,c($x_{now}$),H);
        $x_{best}$ = $x_{now}$;
        best_cost = c($x_{best}$);
        while(termination_criterion_not_meet){
                k=k+1;
                Create(Candidate_N($x_{now}$)$\subset$N(H,$x_{now}$));
                $x_{now}$ = Select_Best(Candidate_N($x_{now}$));
                if(c($x_{now}$) < best_cost){
                        $x_{best}$ = $x_{now}$;
                        best_cost = c($x_{best}$);
                }
                Update(H);
        }
}
```

Figure 5.4. – Tabu Search Algorithm

In the TS application, memory is implemented in several ways. As a form of short term memory, a list of tabu moves, or forbidden bits (*attributes*) was used. Longer term memory was implemented to start *intensification* and *diversification* of algorithm. The mechanism of intensification assumes setting of a new current solution randomly selected from a set of elite solutions, reached during execution of algorithm, and tabu list clearing. This happens only if for a given number of iterations no change in the best solution was detected. Diversification mechanism uses frequency and residence measure to encourage those moves with smaller frequency and higher residence measure. If certain attribute was not changed (residence), or if it was changed (frequency) during certain percentage of current TS run, its change will be forced.

5.3. Optimization Kernel “Nyx”

In general, design of the optical networks implies large number of design variables. The choice of values for each of the design variables in turn leads to NP complexity of the design problem (or optimization). NP hard problems are usually viewed as complex in both time and space (computer memory) terms. In addition to the NP complexity, solution space in the design of optical transport networks is not continuous. These two facts together lead to several possible options in regard to the network design;

- Enumeration of all solutions. Obviously, this is limited to small number of design variables.
- Integer linear programming and derivatives. One will obtain the optimal solution for the problem, but the applicability of such methods is close to that of enumeration techniques.
- Tailored heuristic search techniques. They require significant knowledge about the problem space, or
- Apply general heuristic search technique (GHST).

GHSTs are unique in their ability to perform optimization with limited (rather low) amount of knowledge about the problem. As previously stated, they only require goal function (or objective, optimization function). This is the basis for the “Nyx” optimization kernel.

Following this fact, two basic components of the Nyx kernel are *optimization module* (OM), and *problem module* (*PM*). Their interaction is illustrated in the Figure 5.5.

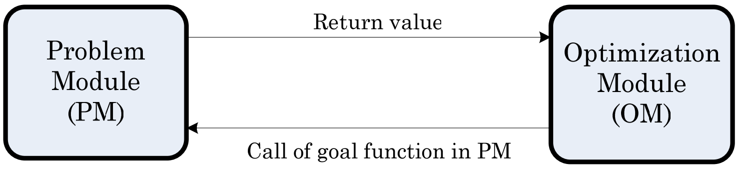


Figure 5.5. – Interaction between PM and OM

The interaction between PM and OM is simple. Problem module is not aware of the optimization procedure. Its only role is to receive encoded solution and asses its quality in terms of optimization goal. On the other side, problem module does not need to know anything about the problem being optimized, except for its quality, which will be determined by the call to the goal function contained within the problem module.

Clearly, the interaction between OM and PM is defined mostly by the type of solution encoding, as the both OM and PM should agree on the ways the encoded solution would be sent to the PM for quality assessment.

Basic goal of the optimization kernel Nyx is fast development of optimization applications. The user is responsible for defining the problem by using predefined set of rules. Defined problem is then attached to the Nyx. Due to the fact that OM offers set of optimization procedures (such as enumeration, GA, SA, TS), for the optimization, a user will have at her/his disposal all of the methods defined within the OM.

In the subsequent sections, Nyx modules and communication between them are explained in detail. This is followed by the Nyx class diagram, and finally by the example of defining the problem in Nyx framework.

5.3.1. “Nyx” Modules

Nyx is composed of following main modules:

- Problem module - PM
- Optimization module – OM
- User Interface Module – UIM

Connectivity and communication between these modules is shown on the Figure 5.6.

UIM implements the user interface, through which end user interacts with the OM or PM. UIM has following main functions:

- Setting and reading of OM and PM parameters,
- Control and management of the optimization. This also means dynamic change of optimization procedure, setting the terminating criterion, inspecting state of the optimization etc.,
- Displaying details and decoding of particular solution.

These functions are actually implemented in either OM or PM, and UIM presents only a proxy that calls required methods in the corresponding modules.

Main functions of PM are:

- Implementation of goal (fitness, objective) function for specific problem,
- Setting of OM parameters.

Interesting note should be made regarding the possibility of setting the OM parameters within the problem module, as its definition is of users concern. This is mainly conceived in order to allow the choice of solution encoding by the problem module, but it also allows dynamic behavior of the optimization procedure. For example, a user can within its problem module, in addition to solution encoding, select optimization procedure and, depending on the quality of the solution, modify desired optimization parameters. Even more, user can change optimization procedure. Thus, in effect, a user has at its hand possibility of creating adaptive optimization procedure.

Main functions of OM are:

- Implementation of general optimization procedures, that can be selected from the UIM, and PM,
- Optimization function (procedure) will call goal function of selected PM, and will expect return value,
- Behavior of optimization procedure is modified by different parameters. Parameters depend on the specific procedure. Optimization procedure parameters can be set either from UIM, or PM. In the latter case, PM should be aware of optimization parameters.

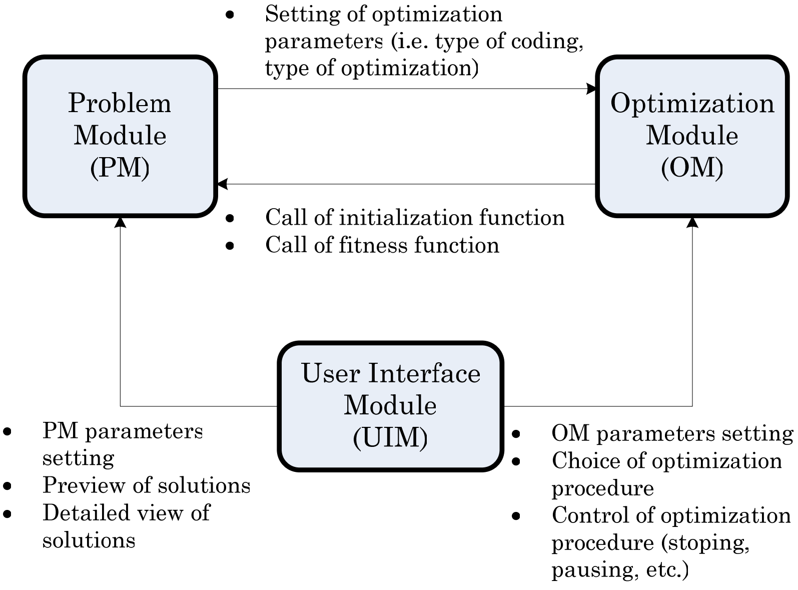


Figure 5.6. – Communication and basic function of Nyx modules

5.3.2. Communication between Modules

Behavior of both PM and OM is modified by their respective parameters. The parameters that can be static or dynamic are encapsulated within the module. In order to allow access to the parameters each module (OM or PM) must implement *Property Exchange Interface* (PEI). The concept of communication between modules by means of PEI is shown in Figure 5.7.

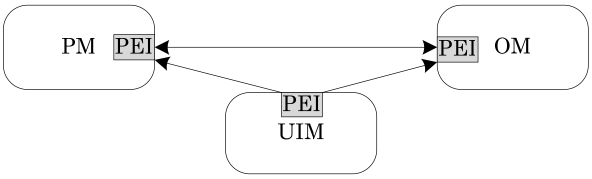


Figure 5.7. – Communication between modules is achieved through PEI

PEI allows access to the list of all parameters within the module. It also allows getting and setting the value of the parameter with the given name. In addition to its value, each parameter possesses access mode that defines permissions, i.e. read only or full access to the property value.

5.3.3. Description of Modules

5.3.3.1. User Interface Module - UIM

Through UIM end users, i.e. application users are able to set and read parameters of both OM and PM. For example, through UIM, as the first step, optimization problem will be selected. This will be followed by the selection of available optimization procedure and definition of optimization parameters, terminating criterion being the most important.

In addition to setting optimization and problem parameters, UIM interacts with PM through problem interface. Problem interface enables call of methods contained within the PM. Example of these methods are `decode`, `detail`, and `save`, which, respectively, present decoded solution, detailed analysis of the solution, or save solution to a file.

Finally, UIM interacts with OM through the optimization interface that enables calls to functions such as `run`, `stop`, and `init`.

List of some main UIM functions is given in Table 5.1.

Table 5.1. – Main functions of the UIM module

Function	Description
`set`	Sets and prints parameter values.
`setproblem`	Chooses optimization problem. It also lists available optimization problems within the given execution context.
`setmethod`	Chooses optimization method. It also lists available optimization methods for the selected optimization problem.
`init`	Starts the initialization of problem module. In turn, this will also start the initialization of the optimization module.
`run`	Starts the optimization procedure.
`stop`	Sets the criterion for terminating the optimization procedure.
`print`	Prints the basic information about the given solution. These are; code word (encoded solution), goal function value, and parameters (if there are any). In this context, parameters are regarded as building blocks of the goal function. They are defined by the problem module, and are optional.
`detail`	Prints detailed information about the given solution.
`decode`	Decodes the solution. For example in the graphical implementation of UIM, this could mean drawing of a solution.

Function	Description
	Command *detail* could include all of the *decode* command plus printing of the information relevant for the goal function.
`save`	Saving and reading of the given solution. Solution is saved in the encoded form.

5.3.3.2. Problem Module - PM

Basically, problem module is a user defined module which contains knowledge about problem which is being optimized. The most important knowledge and the only required about the problem is goal function. Goal function is the main part of any PM.

Fitness function takes single parameter, which represents encoded solution. In general, encoded solution is an array of objects, meaning of which is known only to the PM (goal function defined within the PM) responsible for quality assessment. Though it is not obvious, the main consequence is that problem module must select encoding scheme out of the available set.

Table 5.2 shows methods required by an implementation of the problem module. Short description for each method is also given.

Table 5.2. – Main functions of the UIM module

Method	Description
`initialize`	Should perform initial preprocessing, i.e. reading of the input files, etc.
`fitness`	The method contains complete knowledge about the problem being optimized.
`decode`	Takes a reference to the encoded solution and decodes it into an appropriate way.
`detail`	Takes a reference to the encoded solution, interprets it and presents the detailed information.

Nyx contains the catalog of the implemented problems. Each problem module need to be registered within the problem catalog. Content of the problem catalog can be listed by using UIM.

5.3.3.3. Optimization Module - OM

Optimization module (OM) contains implementation of various general optimization methods. By the term “general” we imply their applicability to wide variety of problems without requiring additional knowledge except for the goal function. However, for each problem certain encoding will be appropriate. For example, if we optimize topology of a network defined by the nodes, solutions can be encoded as binary strings in which each bit corresponds to a link in a fully meshed topology. Value of 1 implies existence of link in a solution, while value 0 implies that the link is not the part of a considered solution. In another example, traveling salesman problem (TSP) inherently requires application of permutational integer encoding in which each value represents the node. Encoded solution thus represents the sequence of nodes for a traveling salesman to visit.

One of the important issues in the design of problem module is the selection of appropriate encoding. Optimization procedure is defined over a given encoding type. Operators of the optimization procedure will be defined differently for different encoding scheme. For example, neighborhood of a solution will be defined differently for binary and permutational encoding. In the same manner, genetic operators have to be defined differently for the different encodings.

Final consequence of the discussion is that selection of encoding defines the set of available optimization procedures. In a way similar to optimization problems, optimization procedures are also registered, but within the catalog of methods (optimization procedures), with encoding type being the main key. This concept is illustrated in Figure 5.8.

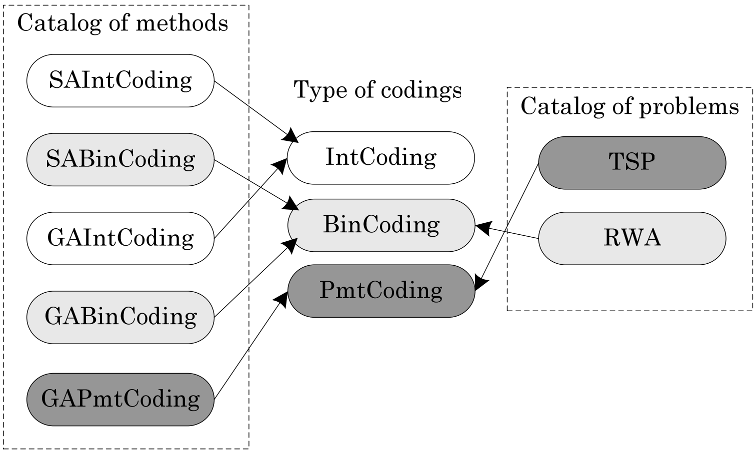


Figure 5.8. – Relationship between problem catalog and methods catalog

Nyx allows binary (`BinCoding`), integer (`IntCoding`) and permutational integer (`PmtCoding`) encoding schemes. As an example, consider a TSP. TSP uses permutation coding, and hence only GA that uses permutational integer encoding can be applied to the TSP. On the other hand, RWA problem uses binary encoding, and thus both SA and GA can be applied to the same problem.

Similar to the problem module, optimization module implements interfaces for communicating to UIM and problem modules. PEI is used for getting the list of OM parameters, reading and setting of their values. In addition, Table 5.3 lists main methods that have to be supported by a optimization procedure.

Table 5.3. – Methods of the optimization procedure

Method	Description
`initialize`	Initialization of optimization procedure, i.e. reading of input data, preprocessing, etc.
`run`	Starts the optimization method for the given problem. The method sequentially calls goal function of the selected problem module.
`save`	Stores the given encoded solution to a file.
`print`	Prints the encoded solution.
`stop`	Sets the terminating criterion.

5.3.4. Nyx Class Diagram

Nyx class diagram is shown in Figure 5.9. The figure shows three modules (OM, PM and UIM), and their respective classes.

Within the PM, all problem modules, for example RWA and TSP, are derived from the class `nProblem`.

In the UIM, only base class `nIO` is defined. This abstract class should be implemented by any user interface. Note that the `nIO` class does not imply the implementation of user interface. Both graphical and text interfaces can be implemented.

In the optimization module classes representing encoding types are defined in addition to the optimization procedures. We assume that binary, integer and permutational integer encoding schemes are sufficient for application to any optimization problem.

Optimization procedures are derived from the base class `nMethod`. In the current version of the Nyx, only GA with basic functionality has been implemented for all encoding schemes. Classes are named `GABinCoding`, `GAIntCoding` and `GAPmtCoding`. If additional functionality is required, new classes will be defined, based on the base classes. Thus, only definition of additional functionality will be required in new classes. This allows simple extensions to the catalog of optimization procedures.

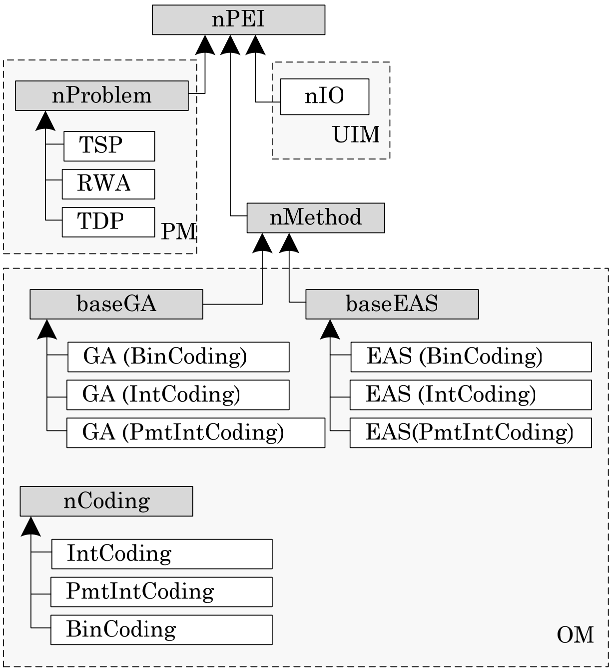


Figure 5.9. – Nyx class diagram

In addition to basic GA, enumeration of all possible solution is also defined for all encoding schemes (`baseEAS`). The basic enumeration procedures start from the first possible solution (this depends on the encoding scheme), and simply iterate through the list of all possible solutions.

5.3.4.1. Encoding Schemes

By the encoding scheme, we assume the representation of solutions for a given optimization problem in a way that is suitable for a functioning of an optimization procedure. The problem module implementer chooses encoding scheme in a way so that it describes solution of the stated problem in the best possible manner.

Within Nyx, all encoding schemes are derived from the base class `nCoding` that contains basic operators. These operators are listed in the Table 5.4.

Table 5.4. – Main operators of encoding schemes

Operator	Description
`++`	Generates next solution form the current one.

Operator	Description
`--`	Generates previous solution form the current one.
`=`	Generates solution equal to the current one.
`==`	Compares the two encoded solutions.
`goForN`	Generates n-th coded solution form current solution.

Note that operators `++` and `--` allow for an exploration of a neighborhood of the current solution. This in turn inherently supports application of GHST based on neighborhood search.

Table 5.5 gives description of encoding schemes implemented within the current version of Nyx, and Table 5.6 shows examples of encodings, and application of operators to encoding schemes.

Table 5.5. – Nyx encoding schemes

Type of coding	Description
`Binary`	Encoding scheme in which solutions are coded as arrays of binary values, i.e. 0 and 1.
`Integer`	Encoding scheme in which solution are coded as arrays of unsigned (non-negative) integer values. Each member of an array is additionally specified by the minimal (default 1) and maximal value.
`Permutational integer`	Encoding scheme in which solutions are codes as arrays of unsigned (non-negative) integer values, but in a way that there are no two equal values. Minimal value is 1, and maximal is equal to the code word length.

Table 5.6. – Application of encoding operators

Encoding scheme	Code word exampl	Operator ++	Operator --
`Binary`	0 0 1 0 1	0 0 1 1 0	0 0 1 0 0
`Integer`	4 1 1 3 6	4 1 1 3 7	4 1 1 3 5
`Permutational`	1 2 3 5 4	1 2 4 3 5	1 2 3 4 5

5.3.4.2. Optimization Methods

In the Nyx, an abstract base class named `baseGA` is defined. The class contains parameters and operators required by the basic implementation of GA. GA is based on three genetic operators; *crossover, mutation* and *selection*. In addition to these operators, each implementation of GA requires method for creation of initial set of solutions. Thus, the base class `baseGA` contains methods as described in Table 5.7.

Table 5.7. – Main methods of the baseGA class

Method	Description
`crossover`	Implements crossover of chromosomes. The operation of crossover depends on the GA parameters such as type of crossover, probability and number of crossover points.
`mutation`	Implements mutation of chromosomes. The operation depends on GA parameter named mutation probability.

Method	Description
`selection`	Implements selection process in which solutions for the next iteration of the algorithm are selected. This operation depends of GA parameters such as selection technique and population size.
`init`	Initializes the GA.
`run`	Starts the GA, i.e. optimization process.

Classes `GAIntCoding`, `GABinCoding`, `GAPmtIntCoding`, are derived form the `baseGA` class and they implement methods shown in Table 5.7. Precise implementation of these methods depends on the encoding scheme. For example, if binary type of coding is used then mutation is implemented by changing 0 to 1 and vice versa.

Current version of Nyx implements optimization method that simply enumerates all possible solutions. Base class for this method is `baseEAS`.

5.3.5. Creation of Problem Module: An Example

The section illustrates generic procedure for creation of problem module. The steps are following;

- Choice of encoding, or implementation of new, and
- Choice of optimization procedure, or implementation of new.

The first step in the creation of problem module is choice of encoding scheme. There are two scenarios; use of existing encoding scheme, or definition of a new encoding scheme. In the first case, required actions are implementation of problem module, and its registration within the problem catalog. After that, Nyx is ready for use.

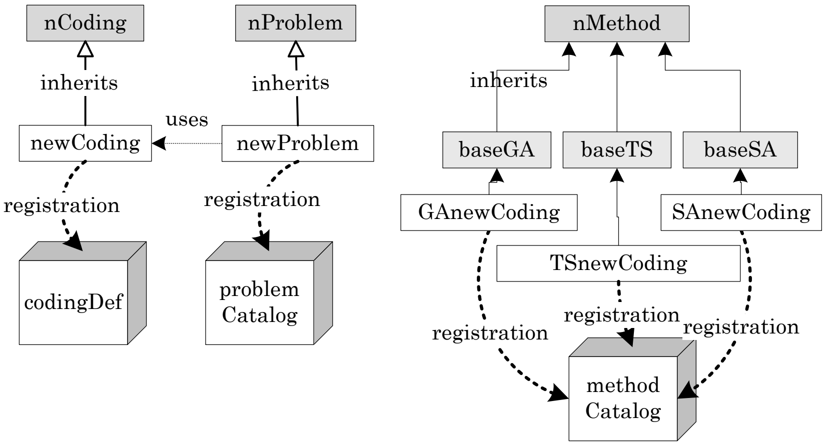


Figure 5.10. – Creating problem module with new coding

In the second case, following actions are required, see Figure 5.10;

- Creation of new encoding scheme, based on the base class `nCoding`,
- Registration of encoding within the encoding catalog (`codingDef`),
- Creation of problem module for the encoding scheme,
- Registration of the problem module within the problem catalog,
- Creation of optimization methods over newly defined encoding scheme, and finally

- Registration of optimization procedure within the method catalog.

Creation of new encoding scheme includes implementation of basic operators as defined in base class `nCoding`. In addition, methods for accessing particular members of a code word (`SetAt`, `GetAt`) should be defined.

Obviously, for a new encoding scheme, one must also implement optimization procedures and corresponding operators. This principle is illustrated in Figure 5.10. It is pragmatic to define abstract class for an optimization procedure which will contain minimal set of operators required by an implementation of the optimization procedure for an encoding scheme. For example, since each GA requires at least crossover, selection and mutation operators, `baseGA` class will contain these methods.

In order to illustrate previous words, we will assume the creation of Traveling Salesman Problem (TSP) problem module. The selected encoding scheme is already available within the Nyx.

TSP problem is defined in the following way:

Input parameters: Matrix M_{nn} where n is the number of towns and $M(i,j)$ is the distance between towns i and j.

Goal: To find the shortest path that starts in the given town, passes through all of towns and returns back to the starting town.

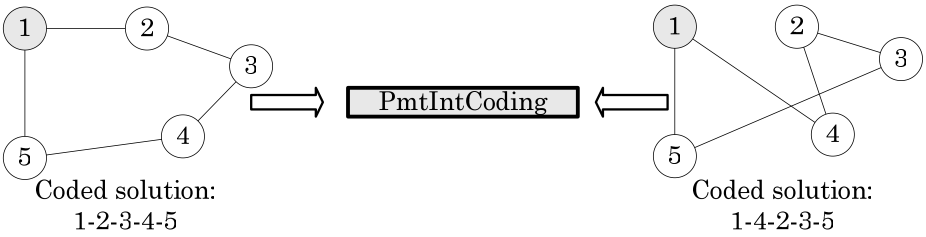


Figure 5.11. – Traveling salesman problem

First step in the creation of TSP problem module is choice of encoding scheme. If we mark all towns with numbers 1, 2, …, n where number 1 is associated to the first (starting) town and n is associated to the last town in the path, then, one order of numbers from the set $S = \{1,\ 2...\ n\}$ is one possible path for the traveling salesman. We can obtain all possible solutions by permuting the elements of set S. From this observation (see Figure 5.11), it is clear that choice of permutational integer encoding is the most efficient.

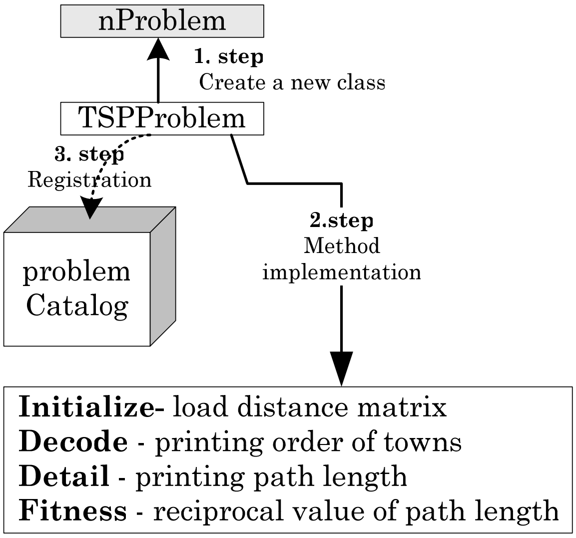


Figure 5.12. – Creating of traveling salesman problem

In the next step, creation of problem module is performed. The problem module, named `TSPProblem` must be derived from the base class `nProblem`, and thus implement all methods defined within the base class. Implementation of these methods assures proper communication with UIM and OM.

Figure 5.12 shows three steps in the creation of new class. The first is creation of class itself. The second is implementation of all methods defined in the base class. For example, in the Initialize method traffic matrix will be loaded from file. Methods detail and decode will be used to print ordering of towns and path length. The main function, in the `baseGA` this is fitness function, quality of particular solution is determined as the inversely proportional to the value of path length. The third, final step is registration of TSP problem module, i.e. `TSPProblem` class within the problem catalog.

For the selected encoding scheme all optimization methods are available.

Execution of program

Execution of the optimization procedure (or program) starts with the initialization of UIM. Inside initializing method, object of class `nOptimization` is created. The object contains problem catalog and catalog of optimization methods (see Figure 5.13). After that, control of the execution is handed over to the user.

In general, the procedure is as follows:

1. A problem to be solved/optimized is chose first,
2. An optimization method is selected next,
3. Optimization and problem parameters are defined,
4. Finally, optimization procedure is initialized before it is started.

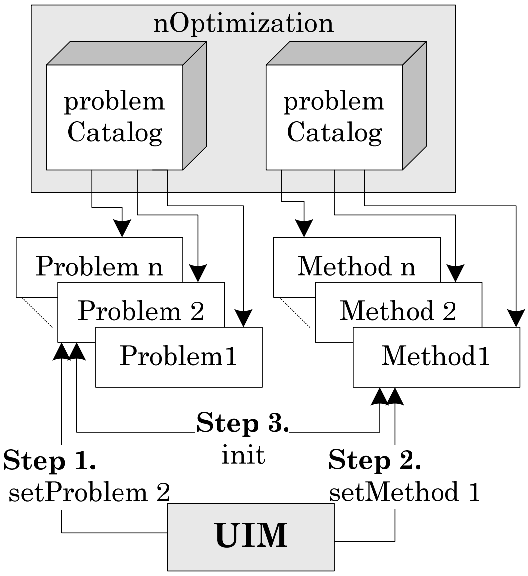


Figure 5.13. – Calling of objects during initialization

After optimization procedure is completed or stopped, it is possible to look at the best solution obtained by the optimization procedure. The solution can be stored in a file, and then optimization procedure can be continued with another optimization method. Figure 5.14 shows state and transition diagram in an optimization procedure.

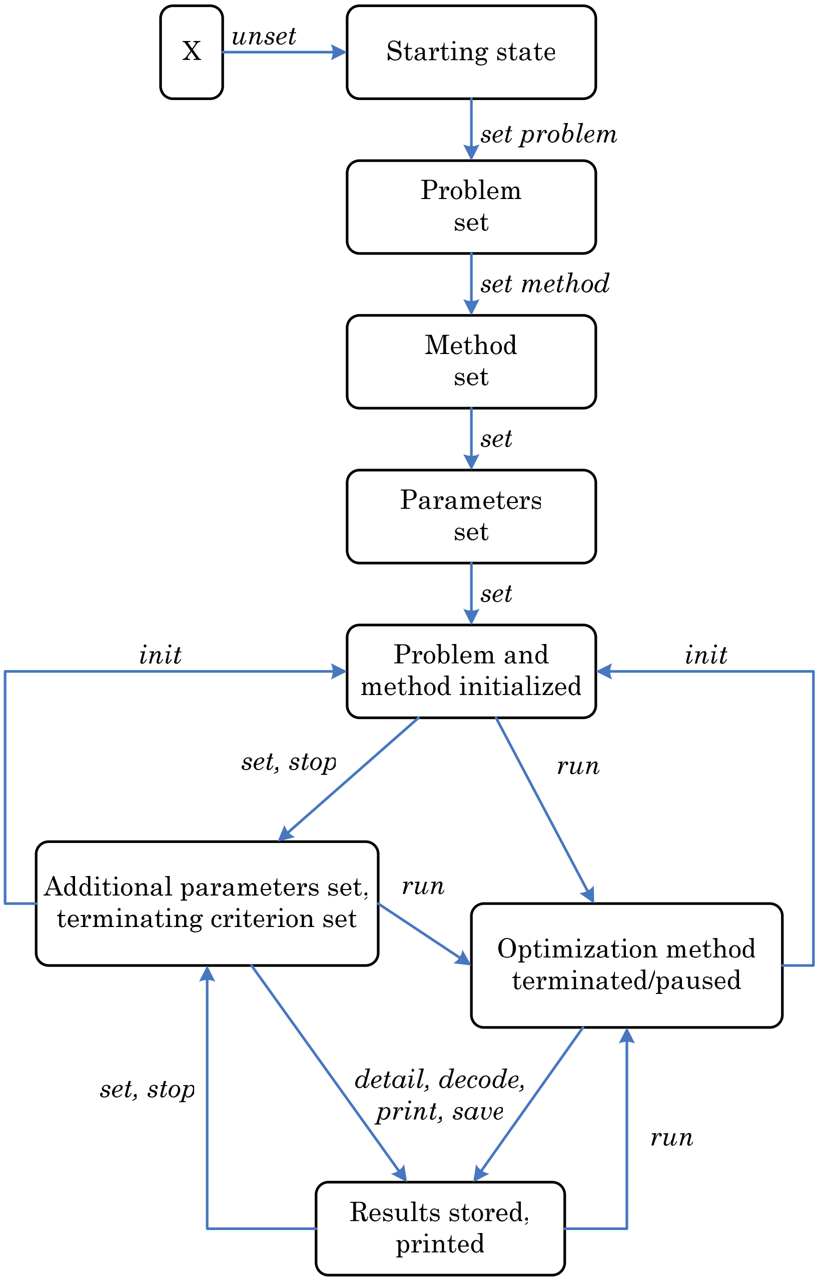


Figure 5.14. – State and transition diagram

5.3.6. Concluding Remarks

Nyx optimization kernel represents generic object oriented framework for implementing optimization procedures based on general heuristic search techniques. It allows fast implementation of optimization procedures. In addition, it allows creation of adaptive optimization procedures.

The architecture of Nyx allows application of different optimization procedures to the same optimization problem. Thus, it is possible to determine the best possible optimization procedure for the given optimization.

In the thesis, Nyx have been used in all network design procedures, aim of which was creation of software model of an optical transport network, on which availability analysis was performed. In the case of mesh networks and optimized routing, Nyx was used for providing the solution to routing (choice of path out of the set of k shortest or choice of independent path out of the set of k shortest independent paths).

5.4. OCS Network

5.4.1. Mesh

The design procedure for the availability analysis of the OCS mesh network has been taken from [PS05]. More detailed description can be found in [DE02][AV28]. In this section only a brief overview is given.

5.4.1.1. Network Structure

The thesis assumes WDM circuit switched transmission network used for carrying IP datagrams encapsulated in a 2nd layer protocol (eg. Sonet/SDH). The conceptual network model is shown in Figure 5.15 and described in [DE06].

The network consists of IPPoP (IP point-of-presence) nodes which serve as IP sources/destinations. They are simplified in this work to the level of IP routers with line cards. Each router can produce traffic to any other router according to the traffic matrix. The traffic matrix is based on the traffic model from the COST 266 action [GN01]. Positions of IPPoP nodes correspond to positions of cities in the core topology (CT) of the COST 266 action [DE07] (Figure 5.15).

Topology and information needed for the traffic model (distances, number of users) to calculate traffic demands serve as input data for the network modeling (Figure 5.15). Traffic estimation for the year 2002 [GN01] was used to calculate the required number of 10 Gbit/s channels.

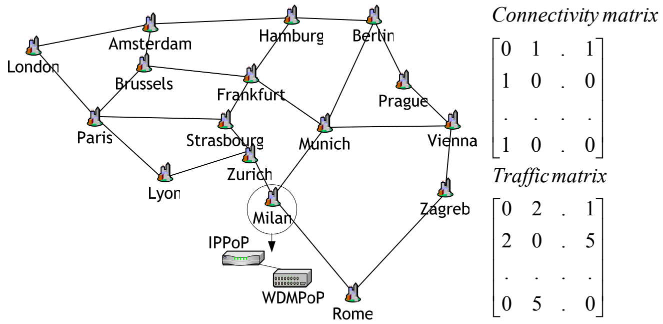


Figure 5.15. – Input data and conceptual network model

WDMPoP nodes serve as a building element of the WDM network. Each IPPoP node is connected to one WDMPoP node which takes the same geographical position as the IPPoP node (city). There is a 10 kilometer distance between IPPoP and WDMPoP nodes at the same location.

5.4.1.2. Node Architecture

A passive WDM network with no space cross-connects and no dynamic reconfiguration possibility was assumed. The used node architecture corresponds to PWN (Passive WDM Network) [AV28]. Figure 5.16 depicts an end-to-end communication between nodes A and C (Figure 5.15). Possible positions of optical cross-connects are indicated, but are not used in the availability analysis.

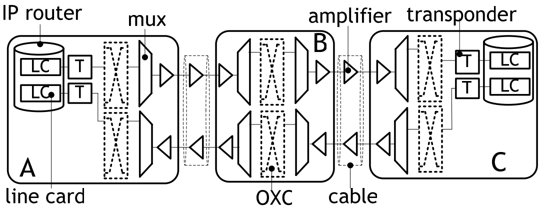


Figure 5.16. – End-to-end communication

Figure 5.17 depicts steps of the network modeling procedure. A more thorough description is given in [DE02].

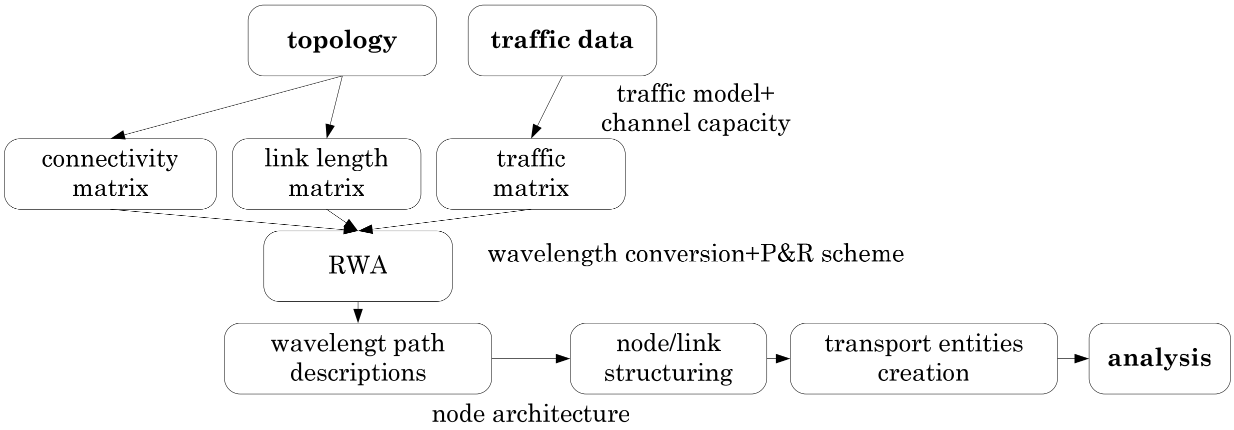


Figure 5.17. – Steps of the network design

Network design procedure takes the topology parameters (connectivity matrix and link length matrix extracted from the node positions) and traffic parameters (traffic matrix) as input data for a routing and wavelength assignment procedure (RWA). RWA assigns a physical path (a list of fibers) and a wavelength to each end-to-end channel from the traffic matrix. The output from the RWA procedure serves as the input for node structuring (assigning necessary equipment to nodes) and link structuring (assigning necessary fibers to cables).

5.4.2. A Procedure for Design of Network with p-Cycles

This section discusses procedures for designing a network with p-cycles. We start with an overview of related work.

In [PC01] an optimal p-cycle network design by using mixed integer linear programming (MILP) formulation has been presented. MILP formulation tries to minimize the total amount of spare capacity, assuming full coverage of units of working capacity. As a pre-optimization step, a set of possible cycle candidates for p-cycle is determined by [GA01]. Similar to [PC03], concepts of working and protection network are dealt with separately. In addition, [PC03] focuses on WDM networks, and presents integer linear programming (ILP) formulation for the WP and VWP networks separately. [PC04] extends the optimal design presented in [PC01] to the IP-layer. An MILP formulation of the problem is given. [PC08] gives an ILP formulation, separately for the VWP and WP WDM networks. It also presents heuristic algorithm for joint routing of the working and spare resources. Finally, [PC09] presents optimal design by joint routing of the working and spare resources.

Here we present procedures for optimal design of p-cycle based networks that can be used with general heuristic algorithms, such as simulated annealing (SA) [GH02], genetic algorithm (GA) [GH01], and tabu search (TS) [GH03]. Thus, the design procedure can be easily implemented within the Nyx framework, as discussed in this chapter.

General heuristic search techniques (GHST) (or procedures, or algorithms) are called general due to fact that only knowledge they require about the problem under optimization is the quality of solution. In order to asses the quality of a solution, GHST use goal function. In addition to objective function, general heuristic search techniques use encoded solutions, and not solutions themselves. Both of these facts, which makes them distinct from classical search techniques, or tailored heuristics, makes them suitable for a quick application to a different classes of optimization problems, or to an optimization problems where the knowledge about the problem being solved is limited.

In general, creation of design procedure with GHST can be divided into two steps:

1. Selection of solution encoding. This is closely related to choice of optimization variables. For example, an encoding may be binary, integer or permutation-integer (explained in detail in chapter5.3.4.1)
2. Selection or definition of objective function.

We consider two possibilities for a solution encoding. In the first one, we use the shortest path routing, and p-cycles are selected by the GHST. In the second one, joint optimization of working and protection resources by GHST is performed.

5.4.2.1. Input Parameters

We assume that the network topology is given. A graph representing topology is denoted as,

$$G = (\mathbf{V}, \mathbf{E}),$$

where **V** is a set of nodes, and **E** is set of links. Mathematical definition of the optical network topology is given in section 2.3.

The second input parameter is matrix with traffic demands which are given in terms of number of lightpaths between each node pair. The traffic demand matrix is denoted,

$$\mathbf{N\Lambda} = \left| N\Lambda_{sd} \right|.$$

An element of the matrix specifies how many lightpaths are required between nodes *s* and *d*. We assume symmetrical traffic demands, and thus,

$$N\Lambda_{sd} = N\Lambda_{ds} \text{ for } \forall (s,d) \in \mathbf{V}, s \neq d.$$

Lightpath *j* between nodes *s* and *d* is denoted as,

$$\Lambda_{sd,j} : s,d \in V, s \neq d, j = 1,\ldots,N\Lambda_{sd}.$$

5.4.2.2. Optimization Variables

Optimization variables are related to:

- Set of paths between pair of nodes.
- Set of p-cycles in a given network topology.

A path is used to route working lightpaths. In general, for each pair of nodes a number of paths can be calculated. A set of paths between nodes *s* and *d* is designated as,

$$\mathbf{\Pi}_{sd} = \left\{ \pi_{sd,i} \right\}.$$

Cardinality of this set is designated as,

$$k_{sd} = \left| \mathbf{\Pi}_{sd} \right|.$$

We assume that this set is an ordered according to the length of the paths,

$$l(\pi_{sd,i}) = l_{sd,i} = \sum_{\forall e_m \in \pi_{sd,i}} l_m .$$

Number of paths between node pair is,

$$|\mathbf{\Pi}_{sd}| = N_{\Pi sd} .$$

For each lightpath $\Lambda_{sd,j}$, a path should be selected. Optimization variable indicating this selection holds an integer value, that represents index of a path between nodes *s* and *d* in a set Π_{sd}. The variable is denoted as,

$$\mathbf{X\Lambda} = \left\{ X\Lambda_{sd,j} = 1,...,k_{sd} : (s,d) \in V, s \neq d, j = 1,...,N\Lambda_{sd} \right\} .$$

For example, in the case of shortest path routing, the problem of selection is trivial, since,

$$|\mathbf{\Pi}_{sd}| = 1 \text{ for } \forall (s,d) \in \mathbf{V}, s \neq d ,$$

and,

$$X\Lambda_{sd,j} = 1 \text{ for } \Lambda_{sd,j} \text{ such that } (s,d) \in \mathbf{V}, s \neq d, j = 1,...,N\Lambda_{sd} .$$

All p-cycle candidates are enumerated in set **P**,

$$\mathbf{P} = \left\{ p_i : i = 1,...,|\mathbf{P}| \right\} .$$

An optimization variable indicates how many times a p-cycle candidate will be selected as a part of a solution set. Thus, the variable holds for each p-cycle an integer value,

$$\mathbf{Xp} = \left\{ Xp_i : i = 1,...,|\mathbf{P}|, Xp_i = 0,...,Xp_{i,max} \right\} .$$

Obviously, a cycle can not be selected an infinite number of times as a part of a solution set. In this regard, $Xp_{i,max}$ represents a maximum number of times a p-cycle p_i can be selected as part of a solution set.

If the routing of working lightpaths is known, then one also knows how many units of working capacity is carried on each optical link. On each of on-cycle links, a single unit of working capacity can be protected by a single instance of p-cycle, while for straddling links, 2 units of working capacity can be protected by a single instance of p-cycle.

If we denote set of straddling links to p_i as ps_i, then clearly,

$$Xp_{i,max} \leq \max \left\{ \max_{\forall e_i \in p_i} \left\{ Nw_i \right\}, \max_{\forall e_j \in ps_i} \left\{ \frac{Nw_j}{2} \right\} \right\} .$$

5.4.2.3. Calculation of Path Candidates

An algorithm presented in [GA05] can be used to enumerate k_{sd} shortest paths between nodes *s* and *d*. In doing this, several limitation criterions could be applied:

- Maximal length of a path.
- Maximum number of nodes the path can traverse (maximal hop count).

In addition, certain path patterns can be forbidden, or imposed.

In the shortest path routing, a simple algorithm of Dijkstra [GA02] can be used. The algorithm gives shortest paths between a node and all of the other nodes in a network.

5.4.2.4. Calculation of Cycle Candidates

In certain cases it is possible to enumerate all of the possible elementary cycles in a given topology and use them as cycle candidates. However, in large networks, this is impractical, and in some cases even impossible.

In order to enumerate elementary cycles in given network graph, an algorithm presented in [GA01] is used. In order to rank cycle candidates, two pre-selection metrics presented in [PC09] can be used. These metrics are based on insights about what makes a p-cycle efficient. The first metric is termed “topological score”, and is defined as,

$$TS(p_i) = TS_i = Nwp_i .$$

Topological score thus indicates number of units of working capacity that p-cycle p_i can potentially protect. This is the reason why this measure is termed *potential protection coverage of a p-cycle.*

A priori efficiency is defined as,

$$AE(p_i) = AE_i = \frac{TS(p_i)}{\sum\limits_{\forall e_j \in E, e_j \in p_i} c_j} = \frac{Nwp_i}{\sum\limits_{\forall e_j \in E, e_j \in p_i} c_j},$$

where c_j is the cost or distance of span e_j. If we assume that,

$$c_j = 1 \text{ for } \forall e_j \in \mathbf{E},$$

then this measure becomes potential protection efficiency,

$$AE_i = PPE_i = \frac{Nwp_i}{Np_i}.$$

The idea is to simply order set of cycle candidates by either *TS* or *AE*, and then choose limited number of the top-ranked candidates. We denote this set of top-ranked candidates as,

$$\mathbf{P}_{op} \subset \mathbf{P}.$$

The number of top-ranked candidates $\left|\mathbf{P}_{op}\right|$ is a variable of the optimization (design) procedure, and should be determined experimentally.

5.4.2.5. Optimization A

In the first type of optimization, working transport entities (i.e. lightpaths), are routed over shortest paths. Accordingly, the only optimization variable is **Xp**. Solutions are coded as simple integer arrays, as depicted in Figure 5.18. The size of the array, as indicated is equal to the number of p-cycle candidates, $\left|\mathbf{P}_{op}\right|$.

We denote solution encoding array as,

$$\mathbf{SE} = \left\{ SE_i : i = 1, \ldots, \left|\mathbf{P}_{op}\right|, 0 \le SE_i \le IntMax \right\},$$

where *IntMax* is a maximum value that can be stored in an integer variable. This value depends on the processor architecture, more specifically, whether processor is 32 or 64 bit. If *nb* is the number of bits that processor architecture uses to hold integer variable then,

$$IntMax = 2^{nb} - 1.$$

Each element in an array indirectly determines number of times a p-cycle p_i will be chosen as a part of the solution set. Optimization variable is calculated as,

$$Xp_i = \left[(SE_i) \bmod \left(Xp_{i,max} + 1 \right) \right],$$

where mod is the modulus function that returns signed remainder after division.

After the p-cycles are determined, complete network is designed, and optimization objective function can be calculated.

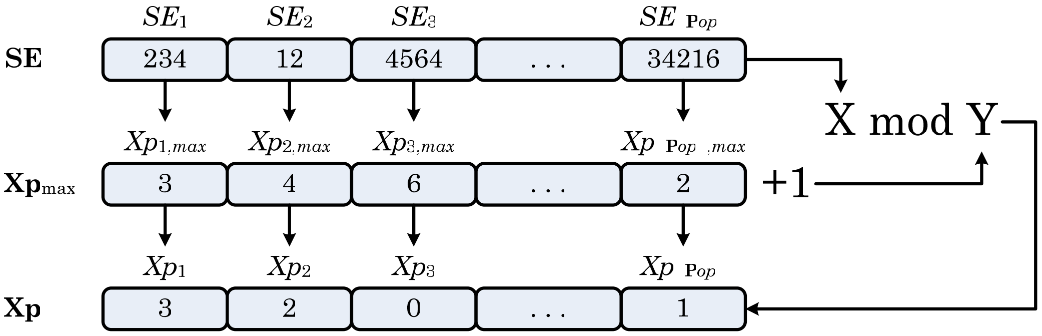


Figure 5.18. – Encoding of a solution in optimization of type A

5.4.2.6. Optimization B

In the optimization of type B, there are two optimization variables. The first one, **XΛ**, determines working lightpaths routing, and the second one, **Xp**, number of instances of p-cycle candidates. Solution encoding is an array of integer values, organized in a way shown in Figure 5.19. The solution encoding array is composed of two parts. First one defines lightpath routing, and the second one p-cycle selection,

$$\mathbf{SE} = \mathbf{SE}_{lr} \cup \mathbf{SE}_{ps}.$$

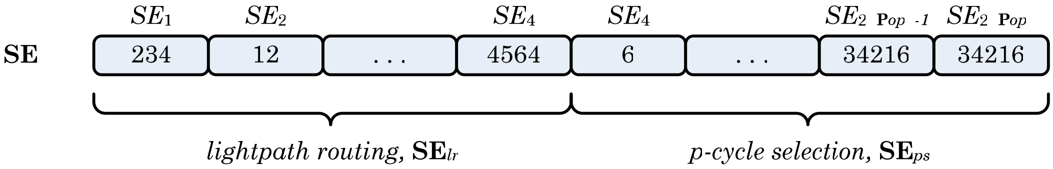


Figure 5.19. – Encoding of a solution in optimization of type B

The size of the first part of the solution array depends on the total number of lightpath required for a network, and can be calculated from the traffic demand matrix,

$$\left| \mathbf{SE}_{lr} \right| = \sum_{\forall (s,d) \in V, s<d} N\Lambda_{sd}.$$

In this way, there is a one-to-one mapping between each lightpath in a network and an element of the solution array. Format of this part of solution encoding is shown in Figure 5.20. Optimization variable is calculated as,

$$X\Lambda_{sd,j} = \left[\left(SE_{lr} \right)_x \bmod k_{sd} \right] + 1,$$

where x is the index of a SE_{lr} array element that corresponds to lightpath $\Lambda_{sd,j}$. It can be calculated as,

$$x = \left[\sum_{k,l \in \mathbf{V}: k \neq l, \left(k \leq s: \text{if } k=l \text{ then } l<d \right)} N\Lambda_{kl} \right] + j, \text{ for } \forall (s,d) \in \mathbf{V} : s < d.$$

The formula assumes that lightpaths are ordered in a way that lightpaths between nodes i and j (i,j), are positioned before lightpaths between nodes k and l (k,l), if

$$k \geq i \text{, and, if } k = i \text{ then } l>j .$$

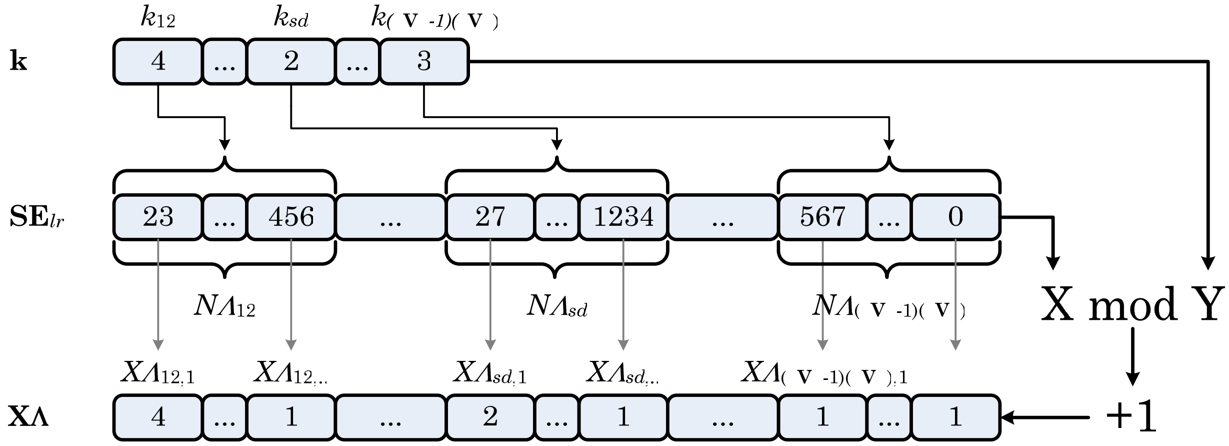


Figure 5.20. – Part of the solution encoding for lightpath routing

The second part of the solution, SE_{ps} is organized as in type A of optimization.

5.4.2.7. Objective Function

Objective function is required in order to asses the quality of a given solution, and to direct the process of searching optimal solutions by GHST. Here we give two functions that can be used as an objective function. In both of them, the goal is to achieve minimal network protection redundancy ratio. The difference is that the first function is more general, due to the fact that it calculates lengths of units of working and protection capacity. If we assume that the length of each link in a network is 1, then we obtain the second case. The first objective function can be defined as,

$$APE_1 = \frac{\sum_{\forall e_j \in \mathbf{E}} l_j \cdot Nw_j}{\sum_{\forall e_j \in \mathbf{E}} l_j \cdot Ns_j} = \frac{\sum_{\forall e_j \in \mathbf{E}} l_j \cdot Nw_j}{\sum_{\forall e_j \in \mathbf{E}} l_j \cdot \sum_{\forall p_i \in \mathbf{P}: e_j \in p_i} Xp_i},$$

where,

APE is actual network protection efficiency,

Ns_j is number of protection units of capacity on a link e_j.

In the second, case APE is equal to,

$$APE_2 = \frac{\sum_{\forall e_j \in \mathbf{E}} Nw_j}{\sum_{\forall e_j \in \mathbf{E}} Ns_j} = \frac{\sum_{\forall e_j \in \mathbf{E}} l_j \cdot Nw_j}{\sum_{\forall e_j \in \mathbf{E}} \sum_{\forall p_i \in \mathbf{P}: e_j \in p_i} Xp_i}.$$

5.5. OPS Network

The design procedure for the availability analysis of the OPS network has been taken from [PS05]. In this section only a brief overview is given.

5.5.1. Network/Node architecture

Network is structured using two generic node types; IPPoP node (IP Point of Presence) and WDMPoP node (WDM Point of Presence), as shown in Figure 5.21. The IPPoP and WDMPoP node paradigm was also used to model the optical circuit switched network (OCS).

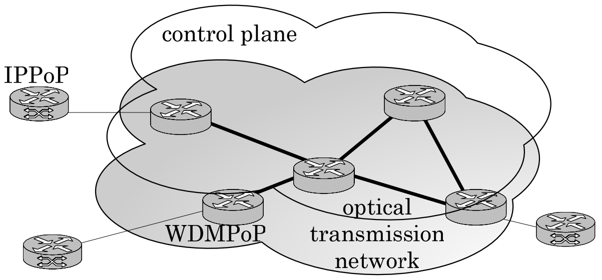


Figure 5.21. – Network architecture

5.5.1.1. IPPoP

IPPoP node implements basic IP layer functionality needed to analyze the optical network performances. This includes initial definitions of traffic demands between each pair of nodes, which serves as the input data for the dimensioning procedure. This functionality is accompanied by the complex traffic source functionality in the simulation phase. The model is flexible enough to be expanded with detailed IP modeling, such as more complex router structure and other advanced IP functionalities.

IPPoP nodes represent communicating IP entities as optical network clients. In the work these clients are determined by the capacity required from the optical network. The idea of the IPPoP node is to represent whole range of possible IP clients from one computer to a complete metropolitan network comprising large number of local area networks and users. In the latter case, optical network supports communication between distant IP networks. The IPPoP node thus can substitute a single user, or a complete town in some reference topology. The IPPoP node dimensioning is determined by the communication capacity between the node (e.g. node *A*), and all other IPPoP nodes in the network (such as node *B*).

An IPPoP node includes sources and destinations of IP traffic (denoted as IPSD) along with the IP router. Each source/destination module models one communication between this and other IPPoP node. IPSD modules are communicating with the optical network using routers. IPSD communication with router is implemented using line cards (Figure 5.22).

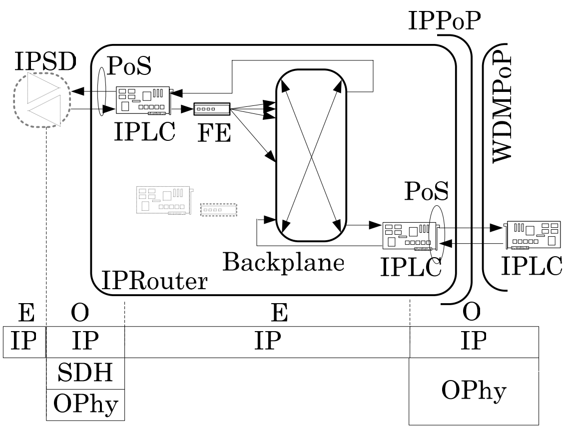


Figure 5.22. – IPRouter architecture

5.5.1.2. WDMPoP

WDMPoP node focuses on optical network node functionality, primarily implementing optical packet switching. Figure 5.23 represents the WDMPoP structure using optical components.

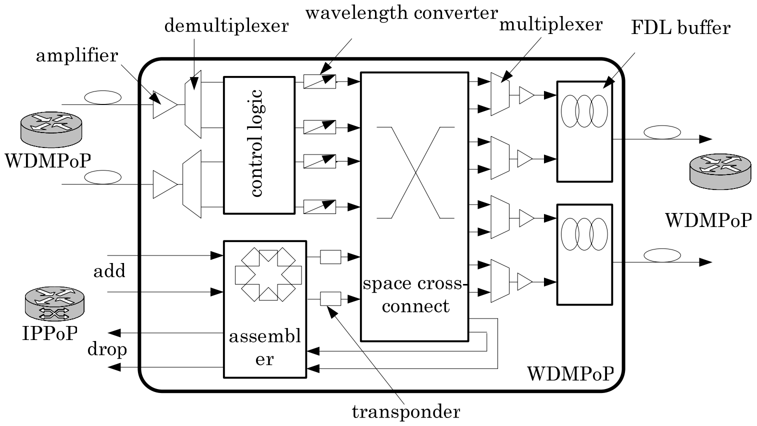


Figure 5.23. – WDMPoP architecture

Input to the WDMPoP node can be WDM multiplexed signal from the other WDMPoP node, or a baseband SONET framed signal from IPPoP (add flows). The input multiplexed signals are de-multiplexed and analyzed in the control logic part at the packet level. The header data along with the buffer state and routing table information determines the configuration of the coding and switching section.

The coding section comprises tunable wavelength converters. The output wavelength depends on the egress packet scheduling. The choice of the output port is determined by the routing table and the state of the port or its occupancy. If all channels (wavelengths) on the output port are occupied, the packet has to be buffered or deflected as a part of congestion resolution scheme [DE03]. The choice of the wavelength and fiber delay line depends on the implemented buffer mechanism [DE04] and/or QoS support [DE05].

In addition to WDM transit signal, WDMPoP node receives the baseband SONET/SDH framed signal. The signal is de-framed in the assembler modules.

5.5.2. Network Dimensioning Procedure

Figure 5.24 depicts used network dimensioning procedure. Input data include topology definition (list of nodes and connectivity matrix), and the traffic model data [GN01]. The aim is to design a network able to support given traffic demands with selected constraints.

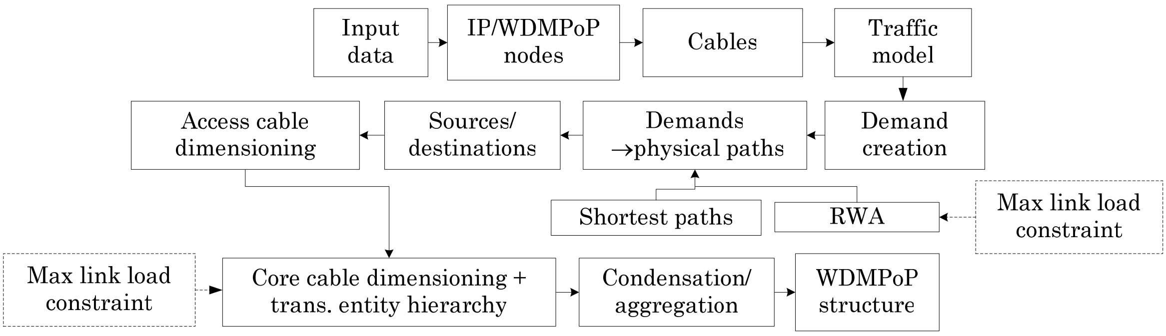


Figure 5.24. – Dimensioning procedure

The first step after data acquisition is creation of network nodes and cables. The dimensioning procedure will produce the necessary internal structures (components). The traffic capacities are calculated using a traffic model. The thesis assumes enhanced population-distance model (*PD*) as described in [GN01] and used in [DE02] and [AV28]. The model can be used with actual geographical node coordinates as they correspond to cities used in the *Cost* 266 proposed topologies [GN01]. The traffic in those cases depends only on node populations and distances between nodes.

Calculated traffic capacities are assigned to demands created between all communicating node pairs (usually all node pairs). The next step is to make connections between demands as the highest part of the logical hierarchy and physical paths comprising nodes and cables. The wavelength conversion option makes difference in this part. In the case of wavelength conversion the shortest path between a node pair is assigned to a demand. Otherwise a routing and wavelength assignment (RWA) has to be made.

A section consists of *n* flows belonging to one demand, each being assigned to different fiber on the cable assigned to the section. A flow can utilize all channels on a fiber in the case of full wavelength conversion. Exact wavelength is dynamically determined on a packet basis upon routing information (determines egress link), state of the channels of the chosen egress link, and state of the buffer if all the channels are occupied and buffer contention resolution is used. Flows without wavelength conversion more resemble OCS wavelength channels which are determined by a wavelength (channel) along with the fiber [AV01]. The fiber dimensioning along with the required functionality (optical packet switching and contention resolution schemes) determines node structure.

5.5.2.1. Deflection Routing

Deflection routing is one of the approaches to contention resolution. The only precondition for deflection is the deflection route entry in the routing table. The network dimensioning does not have to include the additional capacity to support the deflection. This mode will cause very low deflection efficiency as the deflection route ports will be usually occupied by the primary traffic for the route. The alternative is to support the deflection routes by some percentage of capacity they require. This potentially increases the fiber length and component count, but assures larger deflection efficiency.

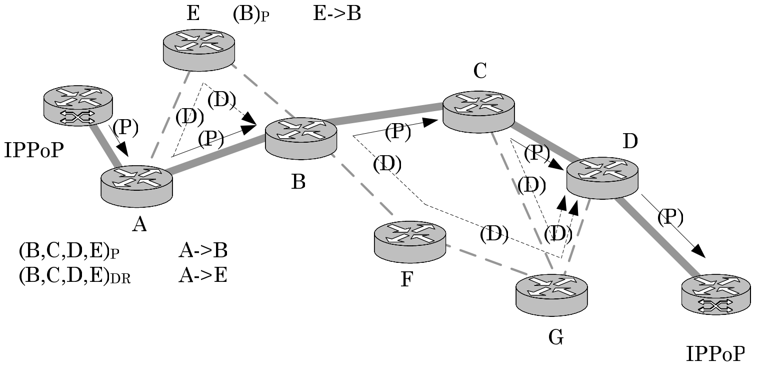


Figure 5.25. – Physical paths of the deflection routing

Figure 5.25 shows deflection routes for the primary route sections. A deflection route is determined for each section of the primary route. It is clear that a section cannot have a deflection section, but a route, as it has to include at least two sections. The deflection route does not have to override just the selected section (this is not always possible), but it can override several sections of the primary route (if possible like in the node B in Figure 5.25). The deflection route has to be link independent with regards to the primary section. The deflection route uses the shortest path between the selected node and any node in the primary path including the selected node itself, but with the minimum deflection hop optimization criteria. This implies that the deflection route quality is proportional to the reciprocal hop count in the deflection route. The reason for such optimization is in better communication characteristics of the primary route compared to the deflection route.

Figure 5.26 depicts additional transport entities used to describe deflection routing. Each primary section (section belonging to the demand route used in the regular case of no congestion) has a deflection route with two or more deflection sections (by definition deflection in one node does not include any routing using the primary route nor the change of a fiber in the cable of the primary route). The deflection flow number does not have to be the same as the number of flows in the primary section as it depends on the percentage of deflection capacity support as well as number and capacity of other demands using cables of deflection route.

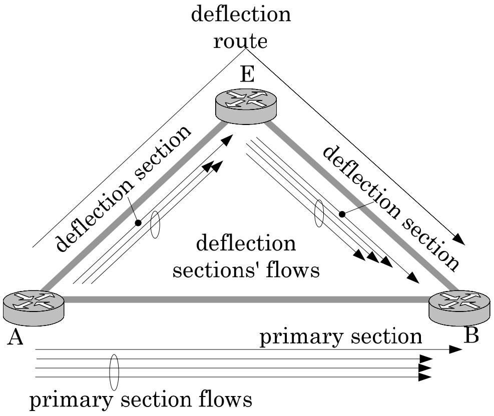


Figure 5.26. – Transport entities of deflection routing

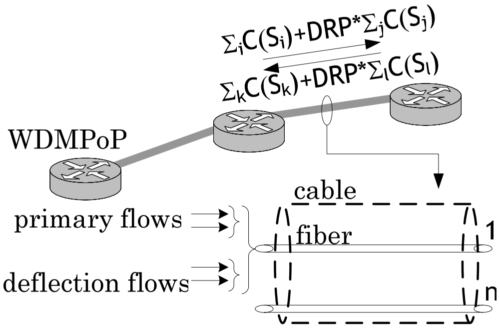


Figure 5.27. – Cable dimensioning with deflection routing

Cable dimensioning procedure is the same as in the no deflection case (Figure 5.27) with the addition of surplus capacity to the regular capacity calculation. This surplus capacity is calculated by determining the deflection routes of all primary routes. Deflection routes are structured using the same transport entity hierarchy. The sum of capacities of deflection sections on the cable is then multiplied by the deflection routing percentage (*DRP*, Figure 5.27) and added to the total capacity of the primary sections on the same cable. There are no guarantees that this kind of dimensioning will support each deflection (even with *DRP* = 1), but with the *DRP* increase the probability of a deflection increases.

6.

Results of Availability Analysis

Design procedures presented in the previous chapter are applied to the COST 266 action topologies [GN01]. In the first section of this chapter availability assumptions are listed. Then, availability results for the COST 266 topologies are briefly presented and compared. Analysis for both packet and circuit switched networks is presented. This is followed by the special section on the availability analysis of the p-cycle based network. The last part of the chapter presents sensitivity analysis of the availability data to the availability results. Sensitivity analysis should identify critical components in terms of the availability. Increasing the availability of such components should result in highest gains in term of the overall network availability.

All results presented in the chapter are obtained by the application of Cosmos tool [AA01], in which MSPN was modeled. Modeling of a optical packet switching part of the MSPN was described in [PS05], while modeling of a optical circuit switching part of the MSPN was presented in [AV32][DE06][DE01][DE02].

6.1. Assumptions

In short, the first step towards the analysis procedure is the network construction. Then the logical hierarchy composed of transport entities is build using the availability model. This allows availability analysis of the network. Once a logical hierarchy has been build availability parameters can be altered to obtain different availability results and thus detect dependencies between the failures of components and transport entities.

In the availability analysis, as presented in the chapter, optical switches within the nodes are not taken into account due to the fact that there are many new technologies available for their implementation for which no availability data exists at the time of writing of the thesis. For some of the switching technologies, one can assume that the availability data is such that allows their omission in the availability analysis.

Component availability data is presented in Table 6.1, and was taken from [DE2]. The availability data originates from [AV23][AV24] and [AV25]. Informal talks with different field engineers within the COST actions 239 and 266 also influenced availability data.

Table 6.1. – Component availability data

Component Type	Failure Rate [fit]	MTTR	Unavail.
Transponder	2000	6	$12.0 \cdot 10^{-6}$
Multiplexer	200	6	$1.2 \cdot 10^{-6}$
Demultiplexer	200	6	$1.2 \cdot 10^{-6}$
Cable [1/km]	100	21	$2.1 \cdot 10^{-6}$
Amplifier (EDFA)	650	6	$3.9 \cdot 10^{-6}$

6.2. Availability Analysis of the COST 266 Topologies

6.2.1. OCS Network

In case of no protection, availability results for the optical circuit switching, presented in Figure 6.1, are slightly higher than that of OPS network (see 6.2.2). The difference can be explained by the inflexibility of OCS network design procedure compared to the one of OPS. Larger differences are visible when comparing DR case in the OPS network and 1+1 protection in OCS network, due to the fact that differences in the installed equipment are also higher.

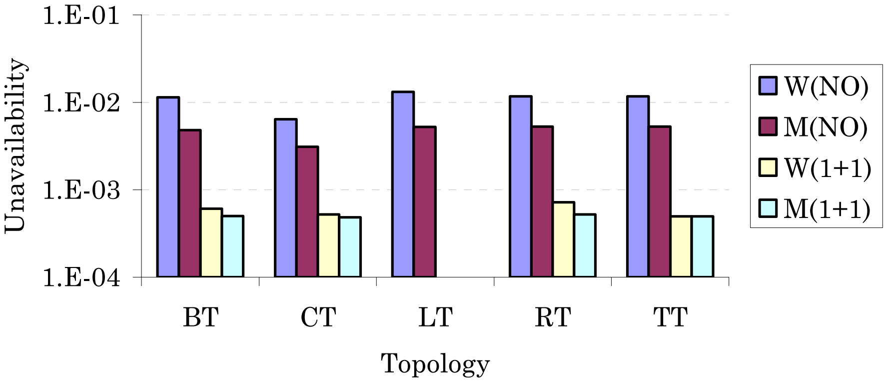


Figure 6.1. – Unavailability of COST 266 topologies (OCS)

6.2.2. OPS Network

Figure 6.2 shows unavailability results for the COST 266 topologies (see appendix A). In the network design process two options were analyzed; without deflection routing (marked with NO) and with deflection routing (marked with *DR*). Figure also shows mean (marked with M) and the worst (marked with W) value of all demands within the network. The analysis was based on the definition of demand (see expression (4.76)). The motivation was in easier comparison with results obtained for OCS network.

Results indicate that in the case without deflection routing CT performs best (lowest unavailability). This is due to the fact that CT is the “lowest” topology in many terms (distances, number of nodes, links, etc.). When assuming deflection routing TT performs best, because of the best connectivity, and thus the shortest deflection routes.

Deflection routing assumed 100% of deflection capacity support. The reason lies in the availability calculation procedure which assumes that deflection route is available for use in case that all elements of the route are in non-faulty state. This constraint would not been meet in the case of lower percentage of deflection capacity.

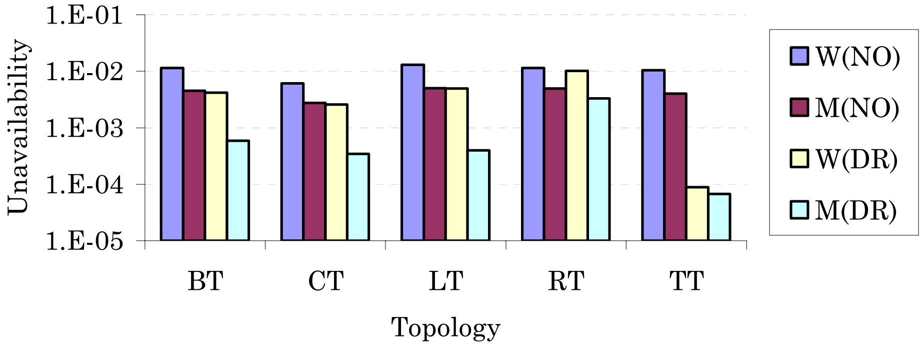


Figure 6.2. – Unavailability of COST 266 topologies (OPS)

6.3. P-Cycle Based Networks

6.3.1. P-Cycle Design

As defined in section 5.4.2.7 the objective function of the p-cycle **Xp** vector optimization depends on the protection efficiency. The protection efficiency (*APE*) is defined as a ratio between capacity needed to support primary communication and p-cycle (protection) capacity. It is clear that the efficiency indirectly denotes the cost of the network design as higher efficiency means less protection capacity under assumption of the same primary communication design. This assumption is valid in optimization A, while in optimization B (see sections 5.4.2.5 and 5.4.2.6) both the numerator and denominator depend on the optimization procedure. It has to be taken into account that the maximization of the *APE* is constrained to solutions that offer full primary communication coverage. Otherwise, the optimal protection efficiency would be zero like in no protection scheme.

However, it has to be noted that with the larger *APE* the expected unavailability of the network increases. This is a consequence of the same initial set of p-cycles **P** and smaller values in the **Xp** vector due to optimization. It means that the same volume of primary communication capacity is protected by smaller amount of protection capacity, or smaller number of p-cycles. This is achieved by overlapping the possible primary communication set between several p-cycles. In other words, parts of p-cycles can be shared among several primary communication units as depicted in Figure 6.3.

If we assume that all primary links carry one unit of communication and choose three cycle candidate to support p-cycles, being $\{A, B, C, D, E\}$, denoted as $PC1$, $\{C, F, G, H, E\}$ denoted as $PC2$, and $\{I, J, K, L, G, F\}$ denoted as $PC3$.

We introduce two types of p-cycle coverage. The first is denoted as topological coverage where each primary link has to be either on-cycle or straddling link to some p-cycle candidate that enters optimization as part of the set **P**. The other coverage is more stringent and is denoted as full capacity coverage, where each unit of primary capacity needs to have at least one unit of protection capacity. The full coverage of one unit of primary capacity does not have to be achieved using just p-cycles on one topological cycle, what is a subject of further discussion. The optimization goal is to minimize the number of such protection capacities to achieve full capacity coverage. This was formalized as a minimization of the vector **Xp**.

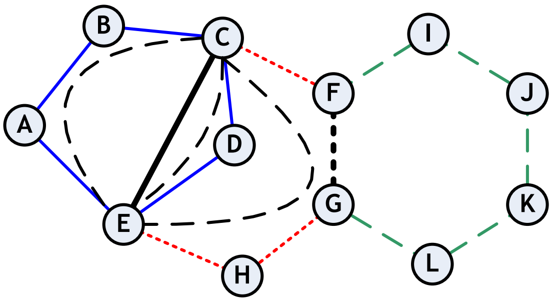


Figure 6.3. – P-cycle candidates

We can conclude that the *APE* maximization yields one unit p-cycle for all three cycle candidates as they provide full capacity coverage. If we calculate with how many p-cycle capacities are protected each of the primary communication links we obtain a following table:

Link	**Primary Capacity**	**P-Cycle Capacity**	**Target P-Cycle**
A-B, B-C, C-D, D-E, A-E	1	1	*PC*1
C-F, F-G, G-H, H-E, E-C	1	1	*PC*2
I-J, J-K, K-L, L-G, F-I	1	1	*PC*3
C-E	1	1 (*PC*1) + 2 (*PC*2)	*PC*1 + *PC*2
F-G	1	1 (*PC*2) + 1 (*PC*3)	*PC*2 + *PC*3

It is clear that all the links are covered with at least one protection capacity either on *P*C1, *PC*2 or *PC*3. This is enough to test full p-cycle coverage. Two links, *C-E* and *F-G* have more than one protection capacity to calculate with. This is consequence that these two links are part of two p-cycles. *C-E* is a straddling link on *PC*1, and an on-cycle link on *PC*2. It is thus covered with 2 protection units via *PC*1 and one protection unit via *PC*2. The same situation repeats with the link *F-G* which is an on-cycle link for *PC*2 and *PC*3 resulting with one unit of protection capacity on each p-cycle. This situation is a consequence of overlapping of p-cycle protection domains as depicted in Figure 6.4.

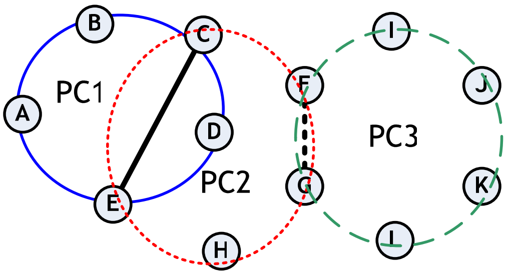


Figure 6.4. – P-Cycle protection domain overlapping

This domain overlapping can be used to minimize requested protection capacity to achieve full primary capacity coverage. The described solution is optimal as we cannot reduce the **Xp** value from any p-cycle, as all p-cycles carry only one unit of protection capacity. On the other hand we can increase the traffic on the links *C-E* and *F-G* and maintain full coverage without increasing the protection capacity. If we set the capacity of the link *C-E* to 3 units and of the link *F-G* to 2 units we obtain the same solution if we take into account p-cycle overlapping. If we take just one p-cycle candidate for each primary link, than the *PC*1 should have at least 2 units of capacity (the first larger number of $Xp_{max}(PC1) = 3/2$ caused by the straddling link is 2). The *PC*3 should also have 2 units of protection capacity.

Obviously we managed to reduce the required protection capacity but have introduced protection capacity sharing in the zones of p-cycle domain overlapping. These zones are clearly the links *C*-*E* and *F*-*G*. The *F*-*G* link has 1 unit of protection capacity but is in the failure domain of the link *C*-*E*. The failure of *C*-*E* (3 primary units) will lock this one unit of capacity on *F*-*G*. The situation is the same with the failure of the link *F*-*G* (2 primary units) which will lock the only protection capacity unit on the link *C*-*E*.

The analysis of a failure of link *C*-*E* loaded with 3 capacity units is depicted in Figure 6.5. The failure locks all *PC*1, and *PC*2 as it is part of both p-cycles. It will also block the protection capacity on the link *F*-*G*. If now the failure of the link *J*-*K* occurs the traffic will be completely lost due to the lock of the part of the *PC*3. This means that the minimization under the sharing assumption (protection domain overlapping) yields full capacity coverage, but without guarantee of a double failure of links on different p-cycles.

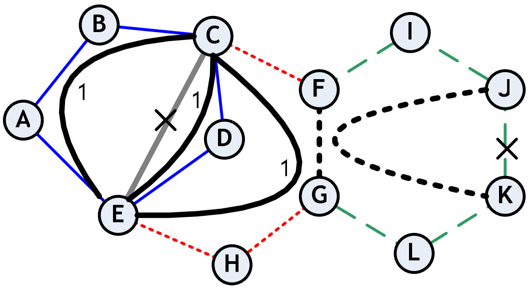


Figure 6.5. – Multiple failures and the sharing concept

We will broaden this analysis onto the Pan European network topologies defined within the EU COST Action 266 and described in [GN01]. We will first focus on the basic topology and evaluate the influence of the definition of the p-cycle candidate set **P** which is further subject to minimization.

The construction of the set **P** comprised following steps:

1. Detection of all cycles in the network,
2. Reduction of the initial set using the number of hops as a constraint,
3. Calculation of the protection efficiency *AE* (A priori efficiency) for each cycle,
4. Sorting of the p-cycle candidate list according to *AE*, and
5. Elimination of p-cycle candidates to remain topological coverage starting from the smallest *AE* candidate

In the step 2 the cycle candidate has to fulfill topological coverage request. This number of hops that delimit the initial set was changed in the range [4, 14] hops. All results are obtained on a network with 16 wavelength, 40 Gbit/s channel capacity and traffic estimation for year 2004 according to [AV04].

The influence of such change on the mean number of a protection capacity unit and the *APE* is shown in Figure 6.6 and Figure 6.7 respectively. The mean sharing number is calculated as a mean value of a quotient of primary capacity and protection capacity that protects it.

It is clear that the number of mean sharing increases with the increase of the hop count. This is a consequence of the increase of the protection domain as the size of the cycle increases. With the larger protection domains the probability of overlapping increases. The mean sharing thus increases.

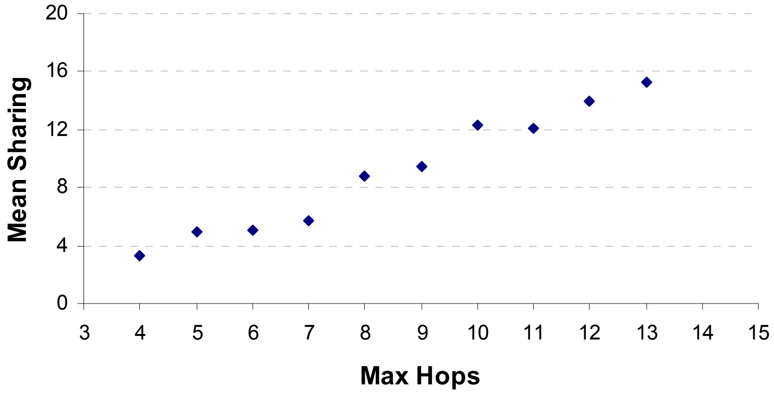


Figure 6.6. – Mean sharing number of p-cycles vs. maximum hop number

On the other hand *APE* increases with the max hop increase, what implies less protection capacity which has to be deployed for full capacity coverage. The APE was calculated assuming the length of each link equal to unity. The length of the links were not taken into consideration in this work.

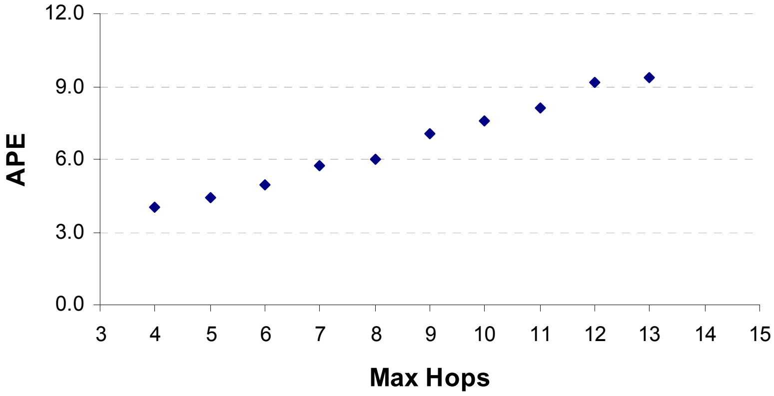


Figure 6.7. – *APE* of a p-cycle network vs. maximum hop number

One of the indicators of the full coverage is the mean number of protection capacity units which cover one unit of primary capacity unit, denoted as the mean protection ratio. This number has to be more or less the same or to vary without a trend with the hop increase as depicted in Figure 6.8.

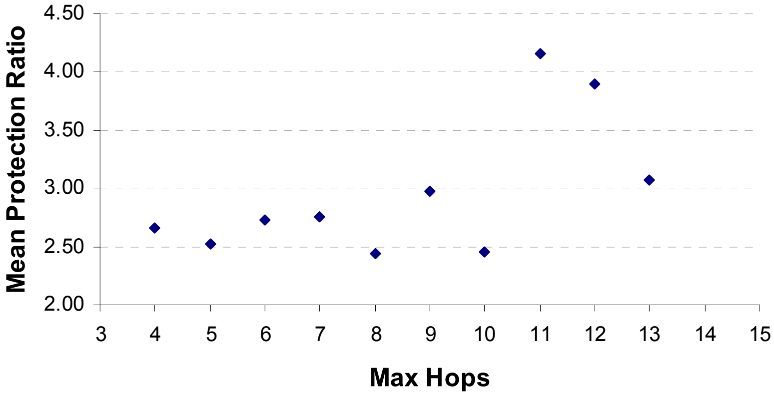


Figure 6.8. – (Un)Dependence of the mean protection ratio on the maximum hop number

The last measure is the unavailability and its dependence on the maximum hop number. All the unavailabilities are calculated as mean values of all logical connection unavailabilities. The unavailability increases with the increase of the hop count what could be expected from the previously explained trends. The protection capacity is decreasing as the design procedure uses the increasing p-cycle overlapping. Thus the number of link sharings increase. The expected number of conflicts during the reservation phase increases, and the mean p-cycle length also increase. We will analyze each of these influences separately.

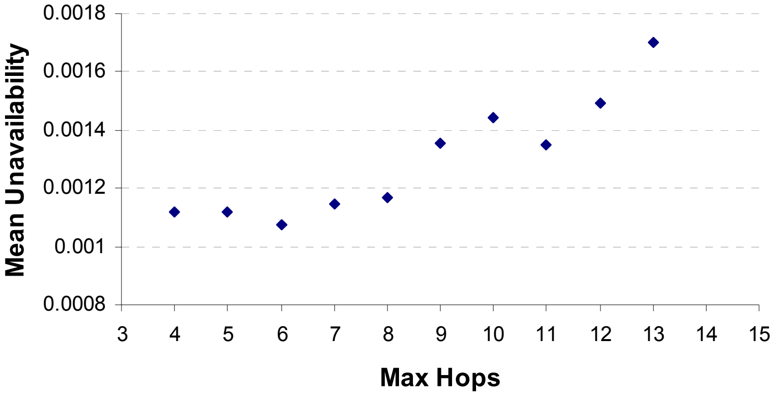


Figure 6.9. – Dependence of the mean unavailability on the maximum hop number

Cable failure causes failure of all transport entities that use it. All primary wavelength channels (*WChs*) thus search the possible protection capacity, being an available p-cycle. All the *WChs* share the same set of possible p-cycle candidates that has to be searched to find the one which is free. The topological coverage assures the existence of this set, and the full capacity coverage assures that the possible connection will be found in the case of a single failure (e.g. one cable cut).

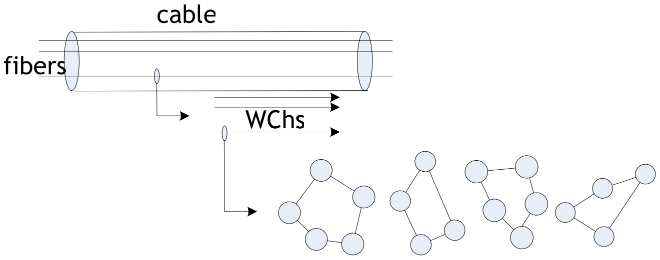


Figure 6.10. – Set of p-cycles corresponding to a wavelength channel group

This set of p-cycles will grow with the number of p-cycle overlapping in the network as each p-cycle will have several p-cycles to choose from. The choice can include several p-cycles as one p-cycle does not have to support the whole *WCh* group (all primary communication on one link).

The search for a possible p-cycle will fail if the p-cycle is not available. Note that with the full capacity coverage this will not happen because some other *WCh* from the group have already taken the capacity in the p-cycle, as all the communication in the case of the single failure should be secured. The unsuccessful reservation thus can arise because of some other primary *WCh* is using the part of the cycle because of the sharing between several primary communication units.

Figure 6.11 depicts number of conflicts that led to unavailability. This is a case where some *WCh* could not allocate protection capacity as it was already taken by some other communication. This can happen only in the case of multiple failures overlapping in time.

Number of conflicts increase with the number of hops as the number of sharing increase as already discussed.

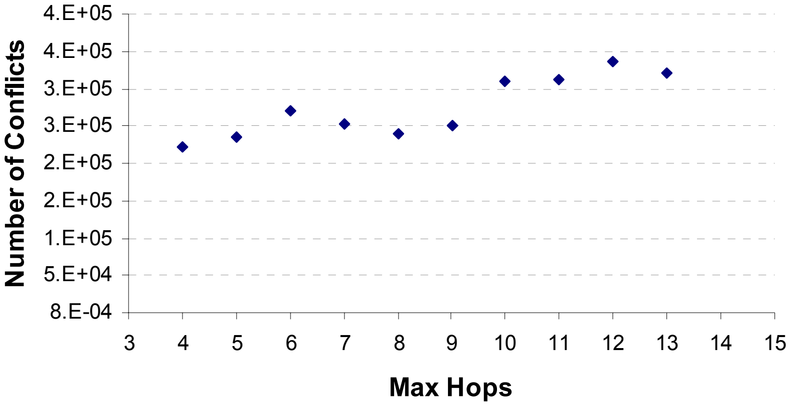


Figure 6.11. – Number of conflict that led to unavailability vs. maximum hop number

It has to be noted that this availability can be very complicated to calculate using analytical expression due to large number of variables. To further elaborate this we will define the term failure domain. In a failure domain of one wavelength channel are all wavelength channels that share any protection resource (link on a p-cycle). Note that in the best case with the zero sharings this applies for all the *WCh*s that are on the same p-cycle. In the case of a straddling link this applies for the whole primary *WCh*s on the p-cycle.

All transport entities that are in the failure domain have to be notified of the release of the shared resource as this can cause reallocation of impaired entities to a newly freed resource.

The slowly increasing number of conflicts cannot cause the detected increase in the unavailability. The cause is the increase of the length of the protection entities. This can be expressed as the mean p-cycle length depicted in Figure 6.12. Note that all the on-cycle link communication has to transverse the whole p-cycle except the damaged link in the case of failure.

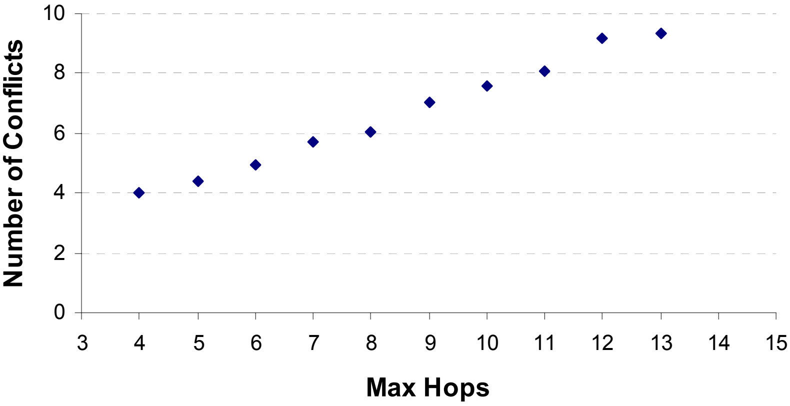


Figure 6.12. – Mean p-cycle length vs. maximum hop number

The straddling links have different mode of restoration as they have to transverse only part of the p-cycle. The choice of the part is arbitrary, but shorter path yields smaller unavailability. These design options are depicted in Figure 6.13.

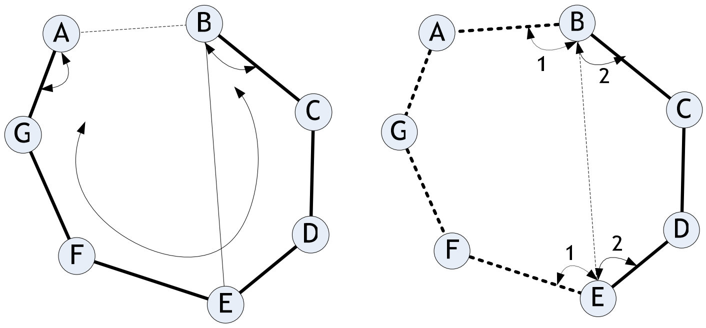


Figure 6.13. – Influence of p-cycle length on the length of the protection path

Two situations with the cut of the on-cycle link *A-B* and with the cut of the straddling link *B-E* are depicted. Note that in the first case the protection has to transverse the rest of the p-cycle composed of 6 hops. The straddling link *B-E* could be used to shorten the protection path to 4 hops, but it means that the straddling link should also have protection capacities what would lead to redundancy. This would actually mean separation of the p-cycle onto two cycles with the link *B-E* as a part of both links. Note that if all the primary capacities are equal to unity the two neighboring cycles could also have the unit capacity as the initial case. This is the consequence of sharing issue. The availability remains the same as the initial design and two cycle design cannot survive the multiple failure case. This situation of a p-cycle decomposition is depicted in Figure 6.14.

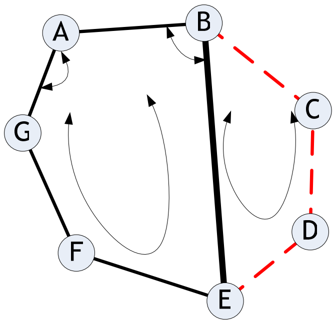


Figure 6.14. – P-cycle decomposition

This work did not analyze the influence of the length of the p-cycles in the optimization, as all the links had the same length. This can be included in the optimization with the change of the objective function as proposed in section 5.4.2.7. The equal link length optimization yields the cheapest solution, but as discussed the protection efficiency does not guarantee good availability. As the length of the links influence the most the unavailability according to the sensitivity analysis, this new optimization constraint would aim at the balance between availability and the cost of the protection. One of the steps in this direction could be the upper constraint on the number of link sharings.

Up to now all the depicted solutions were the optimal solutions obtained after p-cycle set optimization and retrieval of the **Xp** vector values. The differences were thus caused by changing the design options. We will conclude this analysis by examining how mean sharing and *APE* variations influence the mean unavailability. These variations were obtained by causing the sub-optimality of the solution by too small number of generations in the genetic algorithm. Thus the vector **Xp** was not optimal (the sum of its values under the full capacity coverage constraint were not minimal). Figure 6.15 and Figure 6.16 depict obtained results in the form of dependency of the mean unavailability on APE and on mean sharing respectively.

The increase of the *APE* causes increase in the unavailability what is expected as the *APE* relates to the quantity of the added protection capacity. On the other hand the *APE* increase causes the mean sharing increase. Thus with the sharing increase the unavailability increases as discussed before.

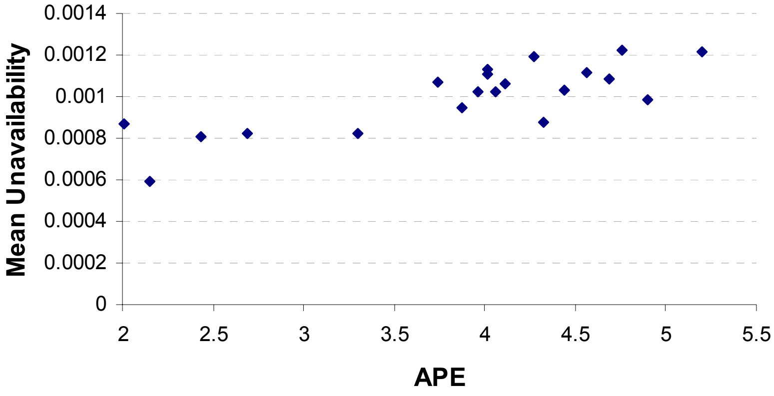


Figure 6.15. – Mean unavailability of p-cycle based network vs. *APE*

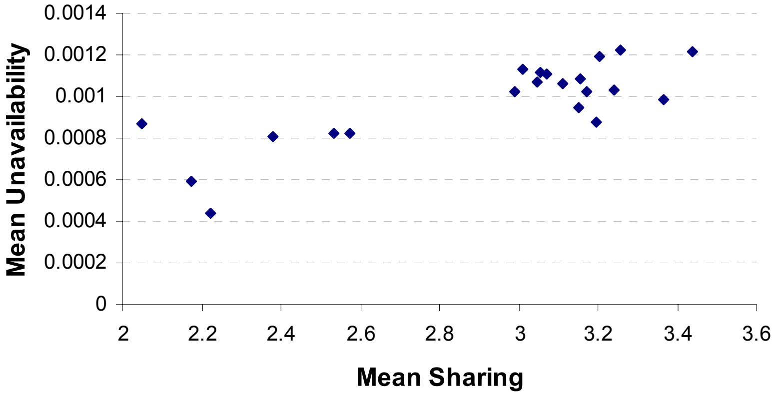


Figure 6.16. – Mean unavailability of p-cycle based network vs. mean sharing

6.3.2. Availability Analysis of Pan-European Network

Availability analysis was conducted on a set of Pan-European topologies proposed within the COST 266 project [GN01]. Table 6.2 depict introduced attributes of the p-cycle solution.

Table 6.2. – P-cycle solution description

Topology	Efficiency	Mean Sharing	Mean Protection Ratio	Mean P-Cycle Length	Conflict #
BT	0.220495	3.17308	2.78739	4.33333	3467559
CT	0.192192	3.49219	2.6549	4.27273	2151379
RT	0.144127	5.663	2.75884	6.90909	4374008

Figure 6.17 depicts the mean network unavailability, while Figure 6.18 shows the worst network unavailability. For each topology three bars are shown. The first, from the left, represents the mesh network without protection, in the middle availability for the mesh with 1+1 protection, while last bar represents p-cycle based network. Worst unavailability is equal to the highest logical connection availability.

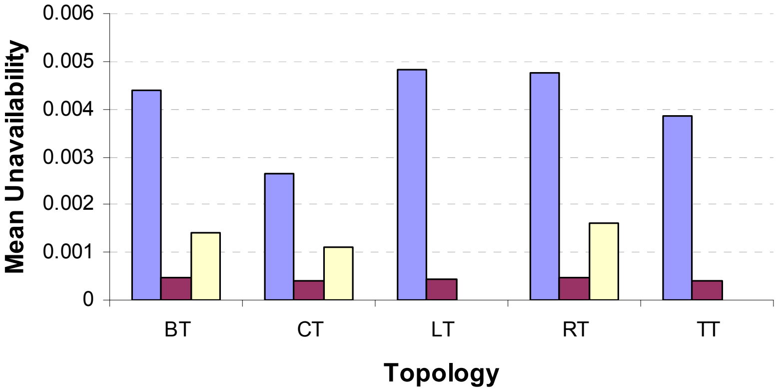


Figure 6.17. – Mean network unavailability

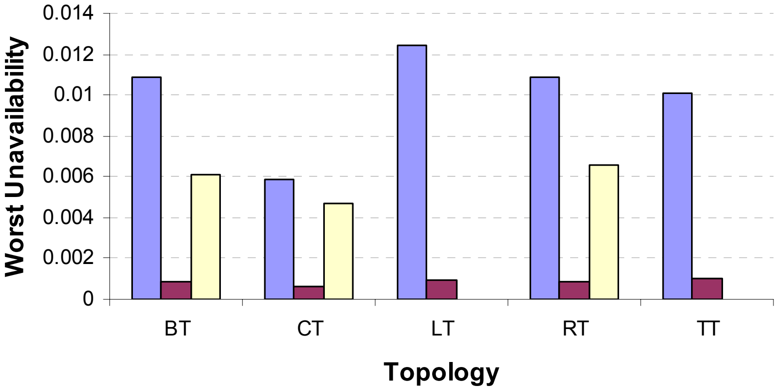


Figure 6.18. – Worst network unavailability

6.4. Sensitivity Analysis

Network availability depends on two key factors. One is related to the network structure itself and includes network topology and the P&R scheme, while the other takes into account features of components used to build a network. Availability of components, their count, and their interconnections influence the final network availability.

The motivation for this work was in the detection of critical component types regarding their participation and influence on the network availability. The knowledge of critical component types and the reasons that lead to tight connections between their availability and network availability can be incorporated in the network design phase to make this influence smaller, and/or to increase the network availability.

Results of the sensitivity analysis for the OCS network have been presented partly in [DE11]. OPS sensitivity analysis was carried in assistance of [AA02].

6.4.1. OCS Network

Sensitivity is generally defined as the dependency of a function on some variable. Strict mathematical definition would be that sensitivity is equal to the function derivation in some point.

Two dependencies have been analyzed in this work. The first analysis included dependency of the transport entity or network availability on the group of variables belonging to the same component type. We analyzed what happens with the availability if we vary simultaneously availabilities of all components of the same type (e.g. amplifier type). In a way, we can speak about sensitivity of input availability data (e.g. component's *MTTFs* and *MTTR*s) to the overall network availability.

The second analysis was focused on the dependence of the availability on just one component. This analysis produces one number as the sensitivity representation. The trend here is in the form of a straight line and the derivation is always the same.

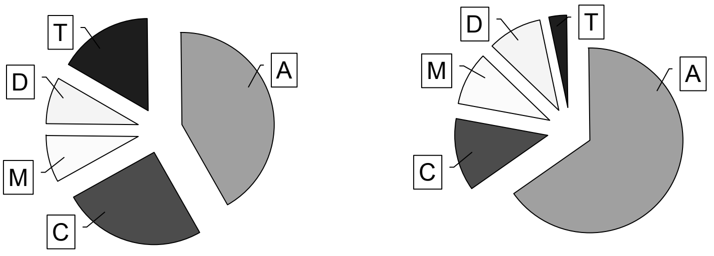
6.4.1.1. Wavelength Path (WP)

Two wavelength paths (WP) have been included in the analysis. The first one is the shortest WP in the network, and the second one is the longest one. The length affects the number of the equipment pieces used by the WP. Table 6.3 summarizes the information on the WPs. Initial availability of the wavelength paths has been determined using the availability data from the Table 6.1.

Table 6.3. – Wavelength paths included in the analysis

	WP Name	**WP Length [km]**	**Initial unavailability**
1	StrasbourgIP->ZurichIP	228	$0.942 \cdot 10^{-3}$
2	LondonIP->ZagrebIP	2610	$6.134 \cdot 10^{-3}$

Figure 6.19a and Figure 6.19b show component count percentages of short and long WP (percentages are expressed considering just the set of analyzed components). The letters represent component types: *A* – amplifier, *C* – cable, *D* – demultiplexer, *M* – multiplexer, and *T* – transponder. Cable percentages are represented by the cable component count, and do not include cable length.



a) short WP **b) long WP**

Figure 6.19. – WP Component Count Percentages

The number of amplifiers increases with the WP length. Longer WP transverses larger number of nodes (this depends on the topology), and includes more cable length in total. More cable length implies more line amplifiers (results presented in the thesis assume 80 *km* distance between two amplifiers).

Figure 6.20 shows dependence of unavailability of WP against component type failure rate (*FR*) variation. Component *FR* was varied in interval [0.2, 5] times of the nominal (starting value). Calculations associated with the long WP are marked with the index 2. It is visible that the optical cables (C) and amplifiers (A) have the strongest influence on the WP's availability.

Amplifier and multiplexer have the same influence on WP unavailability if single component *FR* is changed. A cable will have more influence due to the change of a unit length *FR* as shown in Figure 6.21.

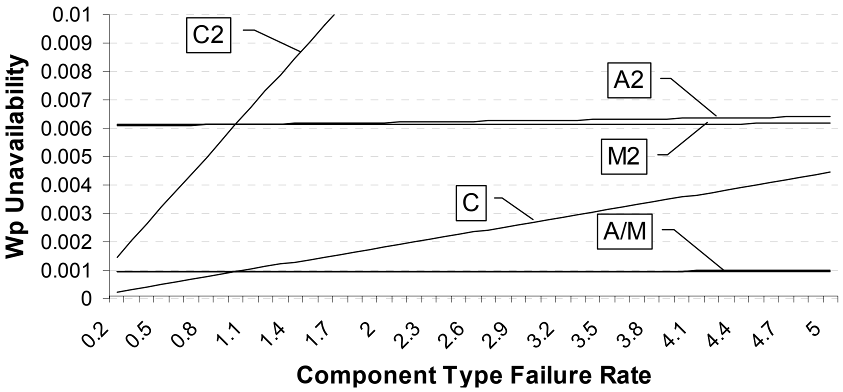


Figure 6.20. – WP unavailability vs. component type *FR* variation

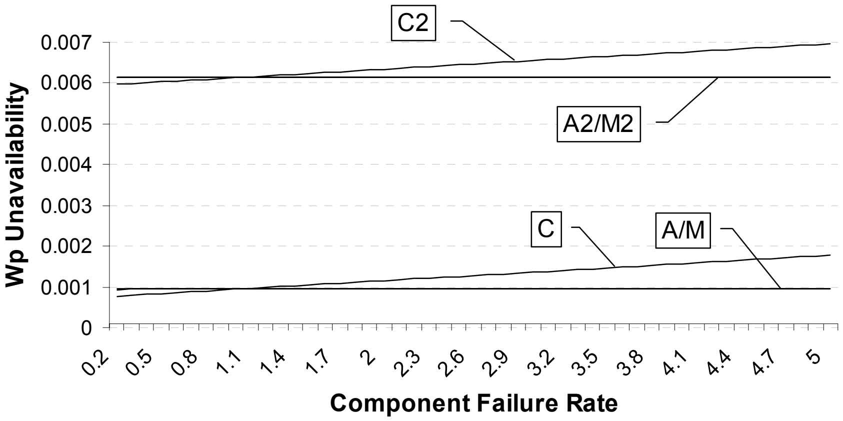
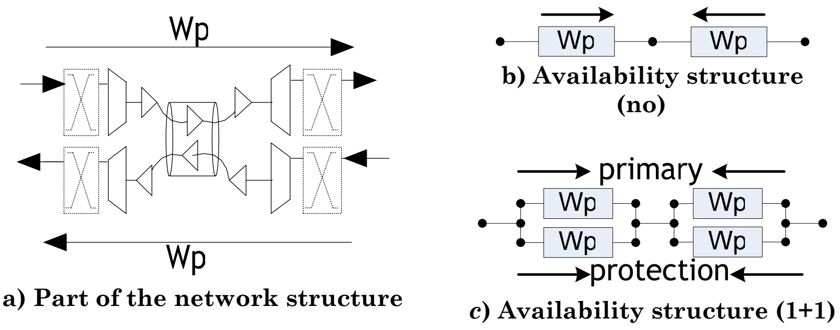


Figure 6.21. – WP unavailability vs. single component *FR* variation

6.4.1.2. Logical Channel (*LCh*)

Figure 6.22a depicts a part of the network structure corresponding to WP. Figure 6.22b and Figure 6.22c show *LCh* availability structure in the case of no protection and 1+1 protection. 1+1 protection assumes end-to-end protection of each WP.



a) Part of the network structure

b) Availability structure (no)

c) Availability structure (1+1)

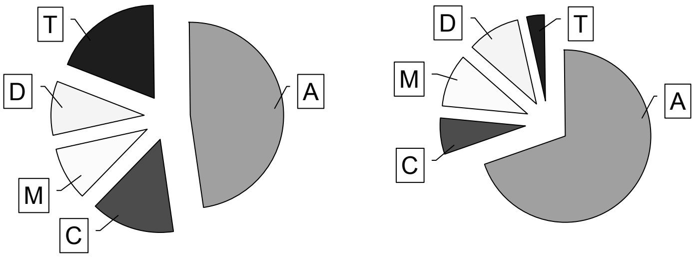
Figure 6.22. – LCh structure

Table 6.4 summarizes the information on the *LCh*s. Initial unavailabilities for the no and 1+1 protection cases have been calculated using the availability data from the Table 6.1.

Figure 6.23a and Figure 6.23b show the component count percentages in the short *LCh* with no protection (*LCh* that contains the longest WP in the network), and long *LCh*. Amplifier is still the component with the largest count, but (de)multiplexer is on the second place. The percentage of the cable count decreases because WPs in both directions use the same cable.

Table 6.4. – Logical channels included in the analysis

	LCh Name	*LCh* Length	Initial unav. (No)	Initial unav. (1+1)
1	StrasbourgIP↔ZurichIP	228	$0.994 \cdot 10^{-3}$	$0.470 \cdot 10^{-3}$
2	LondonIP↔ZagrebIP	2610	$6.397 \cdot 10^{-3}$	$0.508 \cdot 10^{-3}$



a) Short *LCh* **b) Long LCh**

Figure 6.23. – *LCh* Component Count Percentages (no)

Figure 6.24 shows unavailability of *LCh* without protection as a function of component type *FR* (number 2 indicates longer *LCh*). The unavailability performance is similar to that of underlying WPs. Optical cable and amplifiers have the strongest influence on the *LCh*s unavailability in both cases (short and long *LCh*).

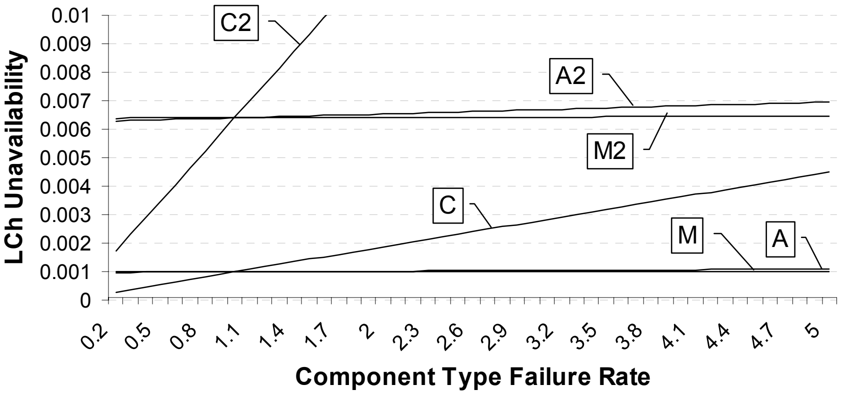


Figure 6.24. – *LCh* unavailability vs. component type *FR* variation (no)

Figure 6.25 shows influence of single component *FR* on the *LCh* unavailability.

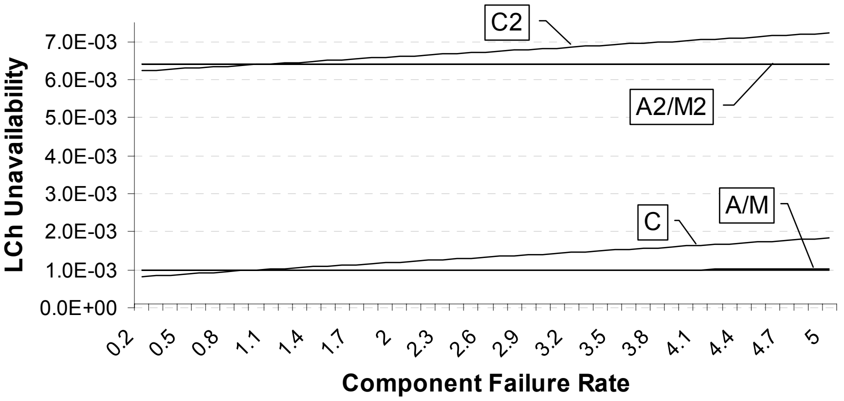


Figure 6.25. –*LCh* unavailability vs. single component *FR* variation (no)

LCh with 1+1 protection keeps similar component count percentages as the unprotected WP with a slight increase in the amplifier percentage. However, the cable influence on the *LCh* availability is stronger than that of multiplexer due to the cable between the IPPoP and WDMPoP which carries fibers with baseband transmission (Figure 6.26). This cable is common to primary and protection WP, and thus represents a weak point of the protection chain. This is the consequence of the protection that is applied only in the transmission network, but not in the access network.

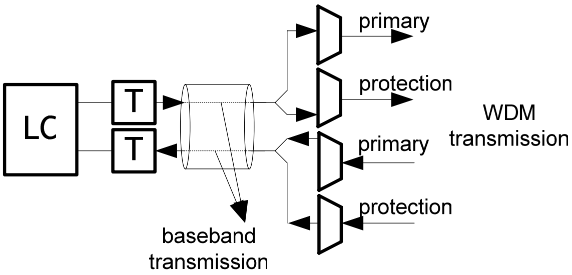


Figure 6.26. – Common cable for the primary and protection WP

The cable type has a stronger influence on the *LCh* unavailability than the multiplexer, despite the fact that multiplexer type has the larger percentage in the *LCh* component count.

Figure 6.27 shows the influence of components *FR*s to the unavailability of *LCh* with 1+1 protection. The figure shows that optical cable is still the most critical component, but this influence is decreased in comparison to case of *LCh* without protection.

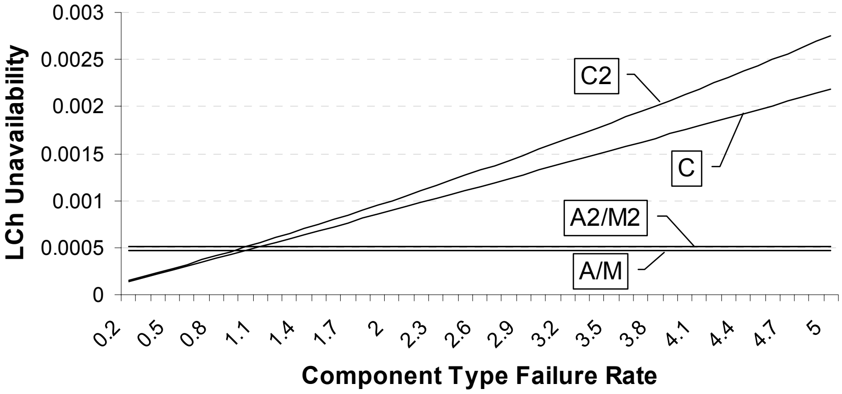


Figure 6.27. – Dependence of *LCh* unavailability on component type *FR* variation (1+1)

Figure 6.28 shows the dependence of *LCh* unavailability on single component *FR* variation.

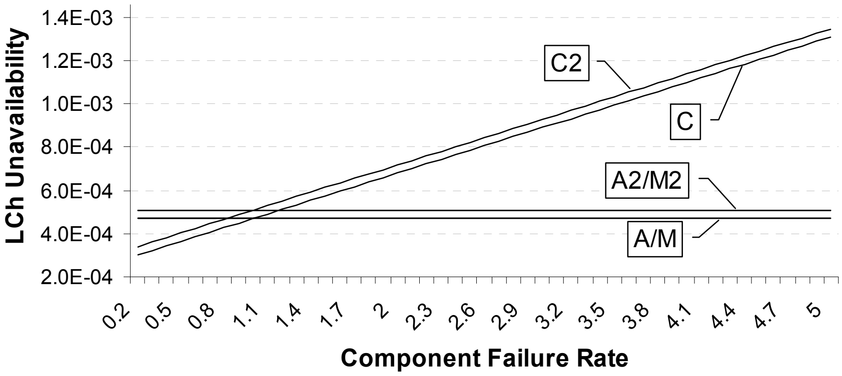


Figure 6.28. – Dependence of *LCh* unavailability on single component *FR* variation (1+1)

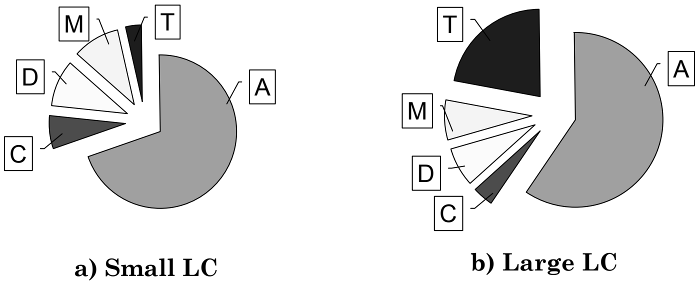
6.4.1.3. Logical Connection (*LC*)

LC availability can be calculated as an *LCh* series or as an *LCh* parallel. *LC* series model can be used to describe e.g. ATM connections where the CBR end-to-end communication is disrupted with one connection tear-down. On the other hand *LCh* defined as parallel is more suitable for describing IP communication where a connection disruption causes rerouting of influenced traffic flows. The influence of the cable is not the same in these cases.

Table 6.5. – Logical connections included in the analysis

	LC Name	*LC* length	*LCh* #	Initial unav. (Ser, no)	Initial unav. (Par, no)	Initial unav. (Ser, 1+1)	Initial unav. (Par, 1+1)
1	LondonIP↔ZagrebIP	2610	1	$6.397 \cdot 10^{-3}$	$6.397 \cdot 10^{-3}$	$0.507 \cdot 10^{-3}$	$0.507 \cdot 10^{-3}$
2	AmsterdamIP↔LondonIP	550	4	$1.870 \cdot 10^{-3}$	$1.631 \cdot 10^{-3}$	$0.639 \cdot 10^{-3}$	-

Two *LC*s are being analyzed. Table 6.5 summarizes the information on the *LC*s. Initial unavailability results are obtained by use of availability data presented in the Table 6.1. Results for the *LC* defined as a series and as a parallel thus will not be different for the small *LC*. Figure 6.29a and Figure 6.29b show component count percentages for small and large *LC*.

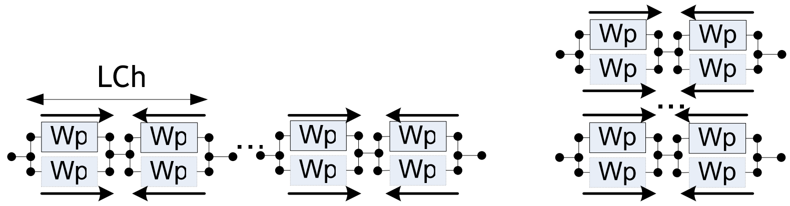


a) Small LC **b) Large LC**

Figure 6.29. – *LC* Component count percentages (no prot.)

The relations between component counts are the same in the case of 1+1 protection. The cable and transponder count percentages decrease.

Figure 6.30a and Figure 6.30b depict *LC* availability structure in the series and parallel definition. 1+1 case is supplemented with protection WPs.



a) Series **b) Parallel**

Figure 6.30. – *LC*'s availability structure

Series

Following figures illustrate dependency of *LC* unavailability on the component type *FR*, for both no and 1+1 protection scenarios. Once again, as in the case of *LCh*, they indicate that criticality of an optical cable can be decreased by proper use of P&R scheme.

In the case of *LCh* series the *LC* unavailability trend is explained by component count percentages. Component type with larger percentage will have stronger influence of the *LC* availability. The results are the same as for WP and unprotected *LCh*.

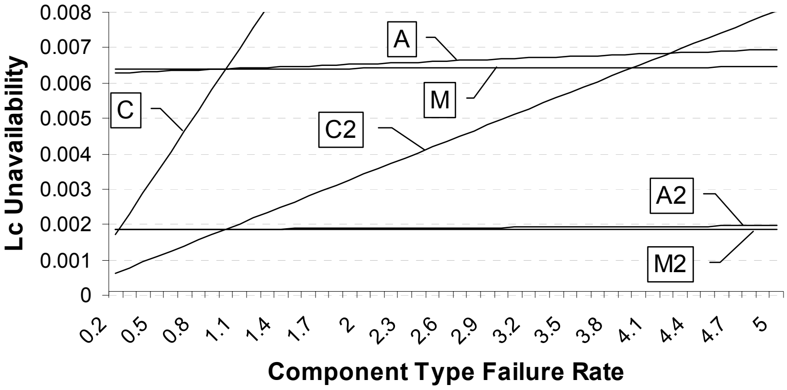


Figure 6.31. –***LC*** **unavailability vs. component type** ***FR*** **variation (no, series)**

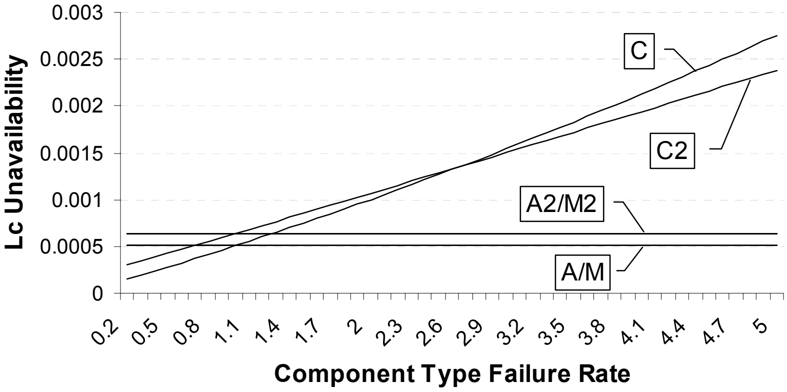


Figure 6.32. –***LC*** **unavailability vs. component type** ***FR*** **variation (1+1, series)**

Parallel

The number of transport entities which share the same component is an important criterion for determining the criticality of the component. The term “to share” in the context denotes usage of the same component by several transport entities (*WP*) at the same time, and is not to be confused with the sharing in the 1:*N* restoration scenarios, or sharings in the context of p-cycle based networks. The amplifier (in addition to optical cable) had the strongest influence due to its largest component count. However it is always being used by just one fiber, and transport entities that use that fiber. The same case is with the (de)multiplexers and the amplifiers. The influence of (de)multiplexer/amplifier depends on the RWA and wavelength assignment because all (primary or spare, but not mixture of primary and spare WPs) WPs between the same pair of nodes do not necessarily use the same (de)multiplexer/amplifier on the way, like they use the same cable. This assumption is true for the fixed routing, which was used to form the physical paths. WPs belonging to the primary or protection group will use the same (de)multiplexer/amplifier only if they use different wavelengths on the same fiber. Moreover, the cable is used by the WPs in the both directions. Transponders are always used by just one transport entity.

The cable is obviously the component that could be shared among the largest number of entities, and thus have strong influence on the entity unavailability. If we define *LC* as an *LCh* parallel, the component sharing becomes important (Figure 6.33).

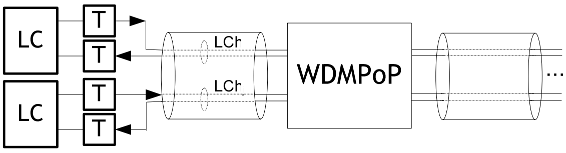


Figure 6.33. – **A part of the** ***LC*** **defined as an** ***LCh*** **parallel**

Figure 6.34 illustrates the *LC* unavailability versus component *FR* for the no protection case. We can now compare two cases. The first, parallel *LC* with no protection can be viewed as the protection on the level of logical connection, as logical channels can be viewed as protecting entities. The second case is illustrated in Figure 6.32, and depicts series LC with 1+1 protection. This case can be viewed as protection on the level of logical channel, as protection is contained within the logical channel.

The comparison of these two cases thus tells at which level it will be more appropriate to employ P&R scheme. In the second case unavailability is lower, and criticality of optical cable is also lower. The conclusion is that application of the P&R scheme at lower layers results in better unavailability performance.

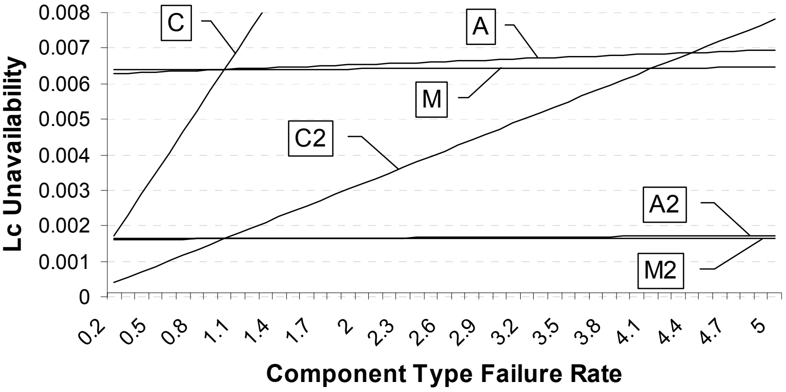


Figure 6.34. –*LC* unavailability vs. component type *FR* variation (no, parallel)

The results are expected – in the small *LC* case the influence only depends on the component count because it has only one *LCh*. In the case of large *LC* the cable sharing among all *LCh*s is visible.

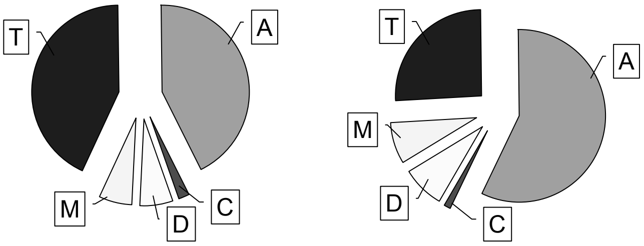
Amplifier type variations in the second case (*LC* with one *LCh*) produces larger unavailability values due to the fact the second *LC* has larger total component count (118), while the first *LC* with several *LCh* has smaller total component count (108).

The component unavailability variation shows the same results for all components in the case of small *LC*, because of just one contained *LCh*. The large *LC* case shows that the cable has the larges influence as the individual component. This is a consequence of sharing. All *LCh*s belonging to the same *LC* use the same cables over the whole path. Any choice of individual cable would produce same results.

In the 1+1 case the component type availability variation produces results similar to those in the *LC* case. The cable influence is the consequence of unprotected access cable.

6.4.1.4. Network

Figure 6.35a and Figure 6.35b show the network component count in the case of no protection and 1+1 protection.



a) No protection **a) 1+1 protection**

Figure 6.35. – Component Count Percentages for network

Network unavailability can be calculated as the worst *LCh* unavailability or the mean value of *LCh* unavailabilities. In this analysis the mean value definition was used.

Figure 6.36 shows the network unavailability (for a no protection case) as a function of component failure type. Letters W and M in the figure indicate network unavailability calculated as a worst or mean *LC* unavailability respectively.

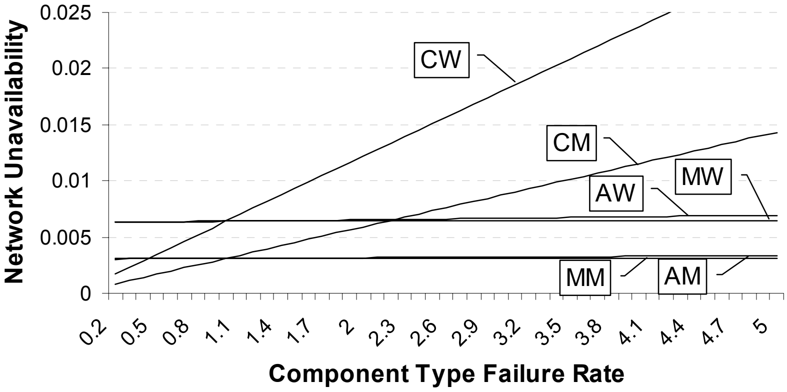


Figure 6.36. – Network unavailability vs. component type *FR* variation

The amplifier (obviously in addition to optical cable) has the strongest influence, and the multiplexer has a little bit more influence on the network unavailability than the cable. This is the consequence of larger multiplexer component count, which dominates over aggregation of entities in the cable.

The analysis of dependence of network availability of one component availability was too weak to be analyzed. The analysis of the 1+1 protection case was omitted due to the long execution time.

6.4.1.5. Conclusion

Different results are obtained in the case of 1+1 protection as component sharing among several transport entities influences availability results. The access cable is shared among all WP (primary and spare) and thus has larger influence than implied by the component count percentage.

The primary influence on the unavailability has the component count percentage. The unavailability of the component type with the highest percentage has the largest influence on the transport entity unavailability. In all cases the amplifier type has the largest component count and thus the largest influence on the transport entity unavailability. However, the component sharing has to be taken into account when analyzing the influence of one component on the entity unavailability. The cable is the component with the largest number of sharings and thus a critical component.

6.4.2. OPS Network

The objective for the analysis was investigation of OPS transport entities and network unavailabilities dependence on the component failure rates. Network unavailability is defined as mean/worst unavailability transport entity unavailability.

This dependence of the structure unavailability on component unavailability is denoted as sensitivity. Sensitivity can be calculated by varying

- One component unavailability, and

- Component type unavailability.

The first approach does not reflect reality as one component unavailability cannot be varied (at least not in such interval of values), while the rest of the component of the same type remain intact. The second approach, for example, may reflect the case where different manufactures offer components with different failure data. The aim was to detect how change in component type unavailability influences the unavailability of communication or network unavailability. These case studies can help in making a trade-off between component price and estimated quality of communication regarding its unavailability.

6.4.2.1. Results

For the analysis core topology (CT) from the COST 266 action was used [GN01]. All the sensitivity results have been calculated using the 32 channel system with 40 Gbit/s channels. The traffic demands were created using approximation for the year 2004. The series/parallel analysis was conducted using homogenous 5 Gbit/s demands between all node pair and 2 wavelength system to force creation of multi-fiber cables between node pairs.

Flow

The analysis included two flows of different length as shown in Table 6.6. Along with the flows length, the expected unavailability is included. The expected unavailability is the flow unavailability with the expected (mean) component unavailability/failure rates values (see section 6.1).

Table 6.6. – Analyzed flows

	Name	Length [km]	Initial Unavailability
Short	StrasbourgWDM↔ZurichWDM	218	$0.498 \cdot 10^{-3}$
Long	RomeWDM↔ZagrebWDM	783	$1.700 \cdot 10^{-3}$

Figure 6.37 and Figure 6.38 depict component counts in the flows. It is clear that the amplifier in both cases has the largest component count what influences its impact on transport entity unavailability. One has to bear in mind that each cable increases the component count by 1, although its influence on the unavailability depends on the cable length and the fact that it is being shared among all fibers between two nodes.

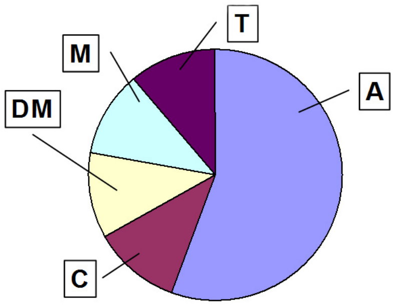


Figure 6.37. – Component count (short flow)

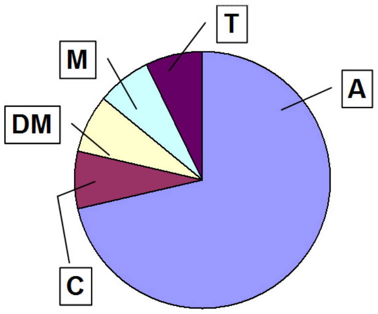


Figure 6.38. – Component count (long flow)

Figure 6.39 depicts a flow unavailability dependence on component type *FR*. The index 2 denotes longer flow. The x axis is linear and expresses a relative *FR*. Each trend is obtained by varying the *FR* of the component type in the interval [0.2*FR*, 5*FR*]. The absolute scale can be obtained by appropriate shifting of trends. Such approach was chosen as the absolute does not reflect the reality where different component have different expected values of the *FR*. The amplifier for example will never have the same *FR* as the *FR* for cable length unit. The goal is to detect the influence of the component *FR* in the intervals that are usual for them. This can correspond to a situation where the same component types can be obtained from vendors with different availability (*FR*) data. The chosen range is 5 times less or more than the expected (mean) value.

The unavailability of the longer flow is always higher than the unavailability of the shorter one due to the larger number of components. It is clear that the cable has the dominant influence on the flow unavailability. The amplifier and the multiplexer share the similar influence. It has to be noted that the trends corresponding to the same flow intersect in the same dot with the *x* value 1. This corresponds to the expected *FR* included in Table 6.6.

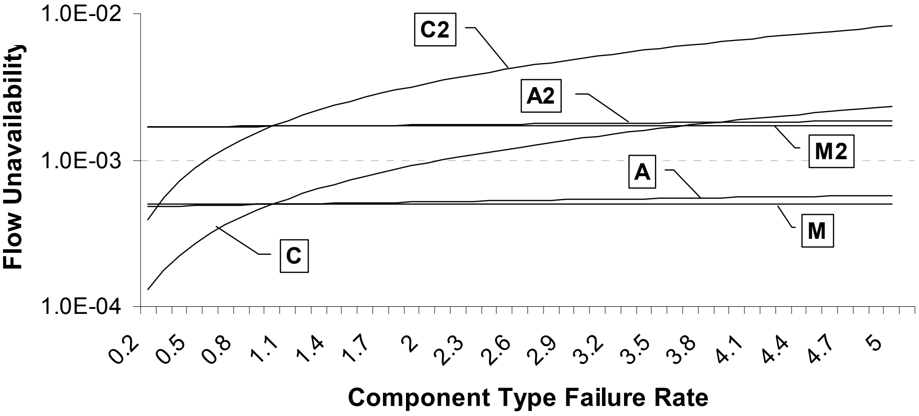


Figure 6.39. – Flow unavailability vs. component type *FR*

The domination of the cable can be easily explained by the fact that the trend is plotted using the unit length cable *FR*. The *FR* of the each cable (FR_{cable}) depends on the cable length (L_{cable}) like,

$$FR_{cable} = FR \cdot L_{cable}.$$

Figure 6.40 depicts the magnified portion of the longer flow trends to show the difference between the amplifier and multiplexer dependence. The amplifier has stronger influence due to larger component count.

The one component trends are similar to the component type trends as flows contain one of the each component, except in the amplifier case. The obtained trends are shown in Figure 6.44. The trends are straight lines as expected. It has to be noted that the straight lines were obtained in the component type *FR* change as all the component types have only one component, except the amplifier which occurs several times due to 80 km of assumed amplifier spacing.

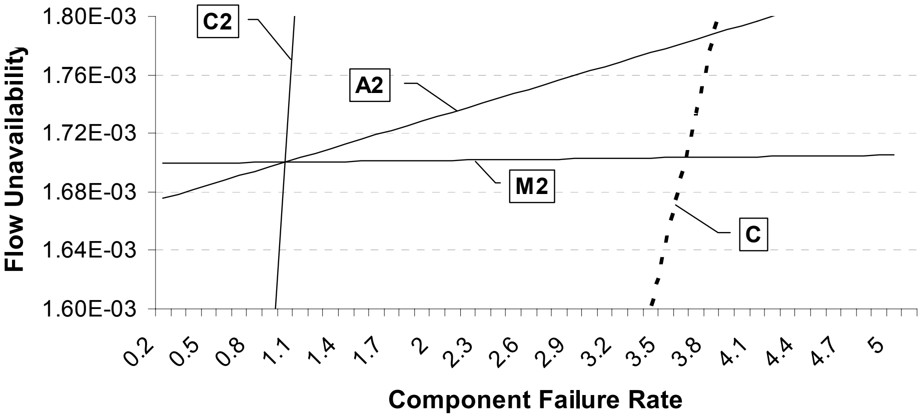


Figure 6.40. – Long flow unavailability vs. component type *FR*

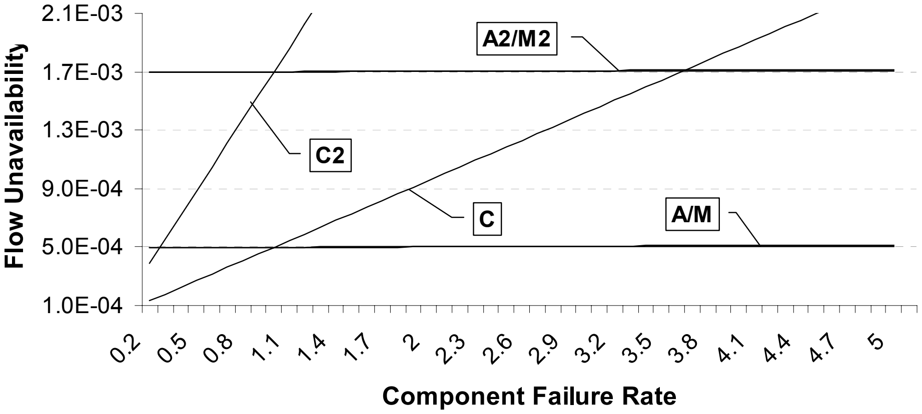


Figure 6.41. – Long flow unavailability vs. component *FR*

Section

As in the flow case, two sections of different lengths have been analyzed. Both sections have only one flow so their sensitivity analysis does not differ from the flow case. The novelty is the possibility of the deflection routing defined on the section level as a deflection route. This part will thus be focused on this design option.

Table 6.7. – Analyzed sections

	Name	Length [km]	Unavailability (NO)	Unavailability (DR)
Short	StrasbourgWDM↔ZurichWDM	218	$0.498 \cdot 10^{-3}$	$7.74 \cdot 10^{-6}$
Long	RomeWDM↔ZagrebWDM	783	$1.700 \cdot 10^{-3}$	$6.59 \cdot 10^{-6}$

Deflection Routing

The analysis was conducted using the same set of section as in the case of no protection. Figure 6.42 and Figure 6.43 depict short and long section structure respectively. The transversed cable lengths have been emphasized as cables have predominant role in the sensitivity analysis. The total length of the deflection route is longer for the long section case, and thus we can expect higher unavailabilities of the long section in comparison to the short section.

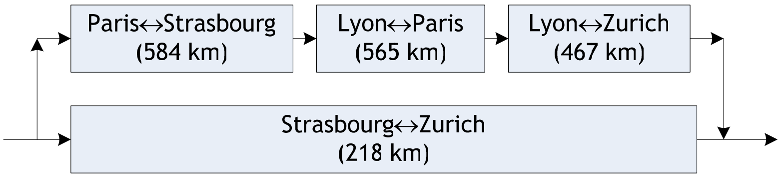


Figure 6.42. – Short Section Structure

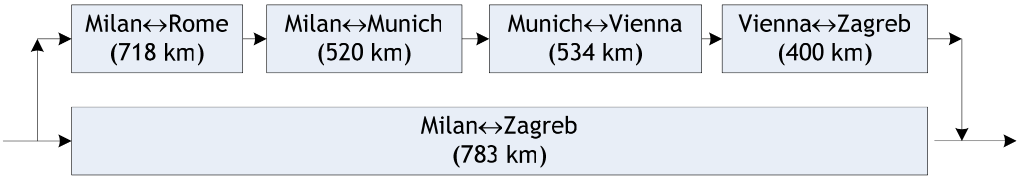


Figure 6.43. – Long section structure

Figure 6.44 and Figure 6.45 depict component count of the short and long section in the case of deflection routing with the 100% of the deflection capacity reservation. The percentage of amplifiers is increasing implying increase of the amplifier influence over multiplexer on the section unavailability.

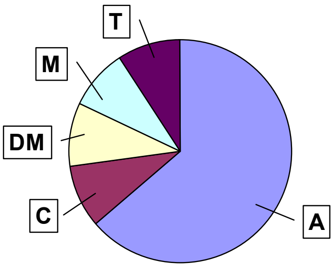


Figure 6.44. – Component count (short section, DR)

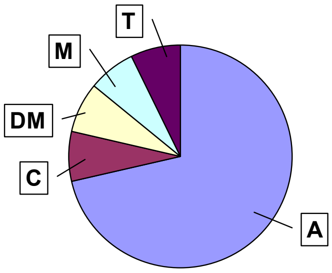


Figure 6.45. – Component count (long section, DR)

Figure 6.46 shows section unavailability dependence on component type *FR*. A clear grouping of results is visible like in the no protection case, implying that deflection routing in terms of unavailability cannot mask the influence of component count. On the other hand, cable remains the component with the strongest influence.

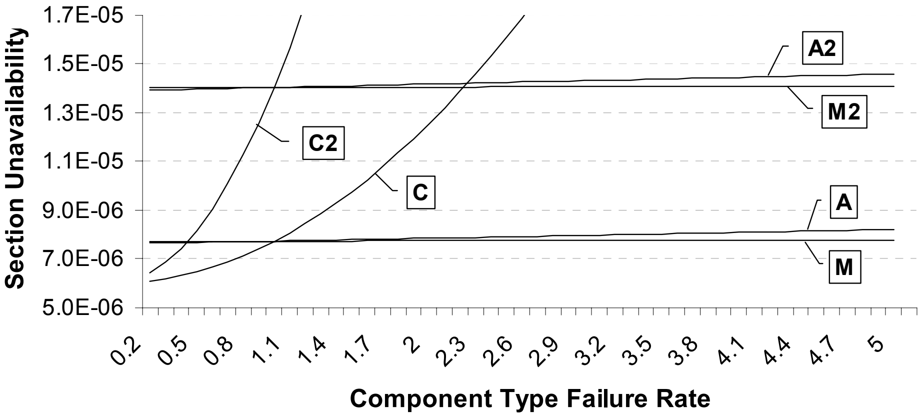


Figure 6.46. – Section unavailability vs. component type *FR* (DR)

The second group of measurements was focused on component failure rate change. Obtained trends are similar to those in the no protection case but with the smaller angles towards the *x* axis. This result is indicative in sense that deflection routing reduces sensitivity of the transport entity unavailability.

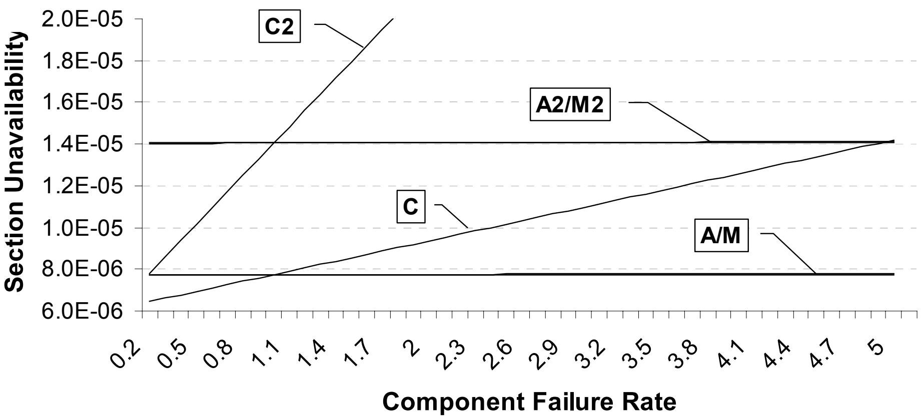


Figure 6.47. – Section unavailability vs. component *FR* (DR)

Series/Parallel

The last part of the section sensitivity analysis was focused on section's logical structure. Default definition assumes section as a series of flows. The precondition of section availability is thus availability of all comprised flows. Such definition may not be entirely realistic as IP traffic demand can be considered available if at least one flow per section exists, or if there is a minimum infrastructure to support a communication. This communication will not be a full capacity, but some reduced capacity transmission. Following this idea, we have defined section as a;

- Series of flows, or
- Parallel of flows,

as depicted in Figure 6.48. In the first case all flows must be available, and in the second at least one flow must be available for a corresponding section to be available.

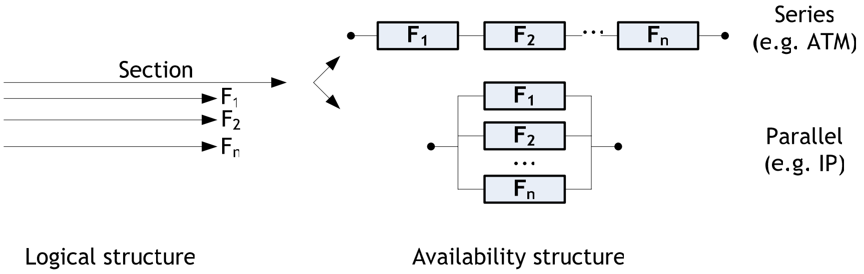


Figure 6.48. – Series and parallel definition of a section

Table 6.8 provides basic information on sections included in the analysis. The emphasis has been moved from the transport entity length to the "size" of the transport entity or the number of sub-transport entities included in the analyzed one. In this case the size of the section is determined by the number of comprised flows. Two sections with one (denoted as small section) and with two flows (denoted as large section) have been chosen. The expected unavailabilities are determined by the used equipment and the availability structure. The parallel structure yields difference in results only with the large section.

Table 6.8. – Analyzed sections

	Name	**Flow #**	**Length [km]**	**Unav. (ser.)**	**Unav. (par.)**
Small	AmsterdamWDM↔HamburgWDM	1	519	$1.141\cdot10^{-3}$	$1.141\cdot10^{-3}$
Large	RomeWDM↔ZagrebWDM	2	345	$0.805\cdot10^{-3}$	$0.730\cdot10^{-3}$

Figure 6.49 and Figure 6.50 depicts component count of the small and large section. The amplifier remains the component with the highest component count.

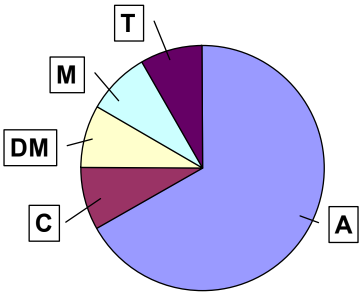


Figure 6.49. – Component count (small section)

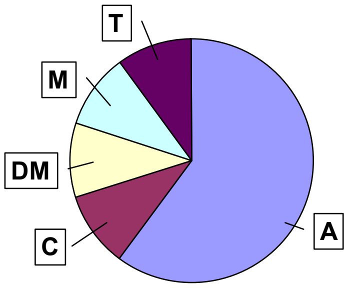


Figure 6.50. – Component count (large section)

Figure 6.51 depicts the analysis of the dependence of section unavailability on component type *FR*. The index 2 denotes large section.

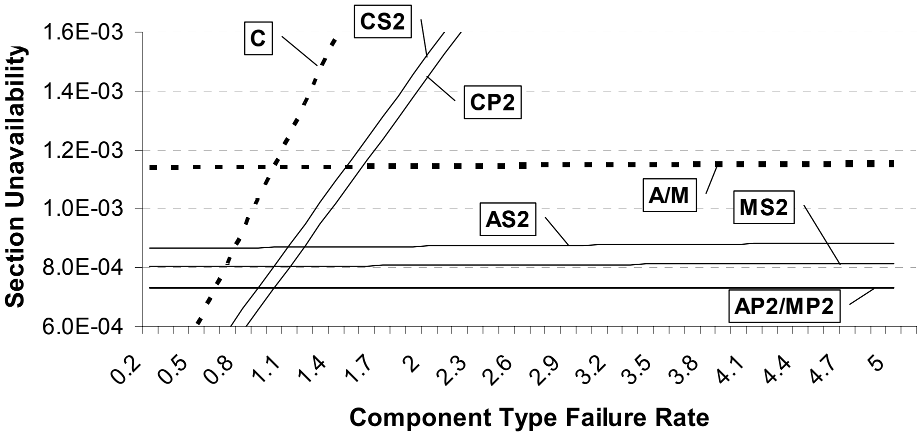


Figure 6.51. – Section unavailability vs. component type *FR* (5 Gbit/s)

Figure 6.52 depicts the analysis of the dependence of section unavailability on component *FR*.

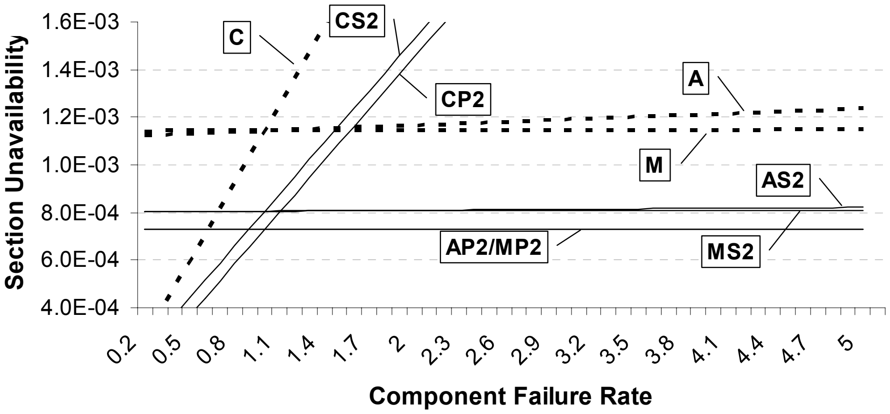


Figure 6.52. – Section unavailability vs. component *FR* (5 Gbit/s)

Route/Demand

The analysis of route and demand transport entities has been conducted jointly as each demand contains only one route as a design option.

Analysis included two demands of different lengths to show the influence of difference in component type count on the “rapidness” of unavailability change.

Table 6.9. – Analyzed demands

	Name	Length [km]	Unavailability (no)	Unavailability (DR)
Short	StrasbourgIP↔ZurichIP	218	$0.546 \cdot 10^{-3}$	$5.57 \cdot 10^{-5}$
Long	AmsterdamIP↔MilanIP	1565	$3.539 \cdot 10^{-3}$	$79.30 \cdot 10^{-5}$

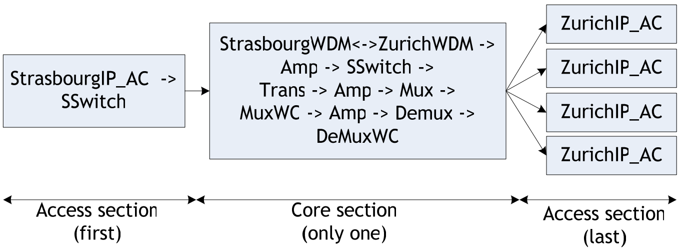


Figure 6.53. – Short demand equipment

Last access section of short demand has four flows what does not imply increase in capacity from first access section, but that the access cable of the Zurich node has more traffic and requires four access links. This demand can thus use any of those four baseband links and thus has four flows in the last access section.

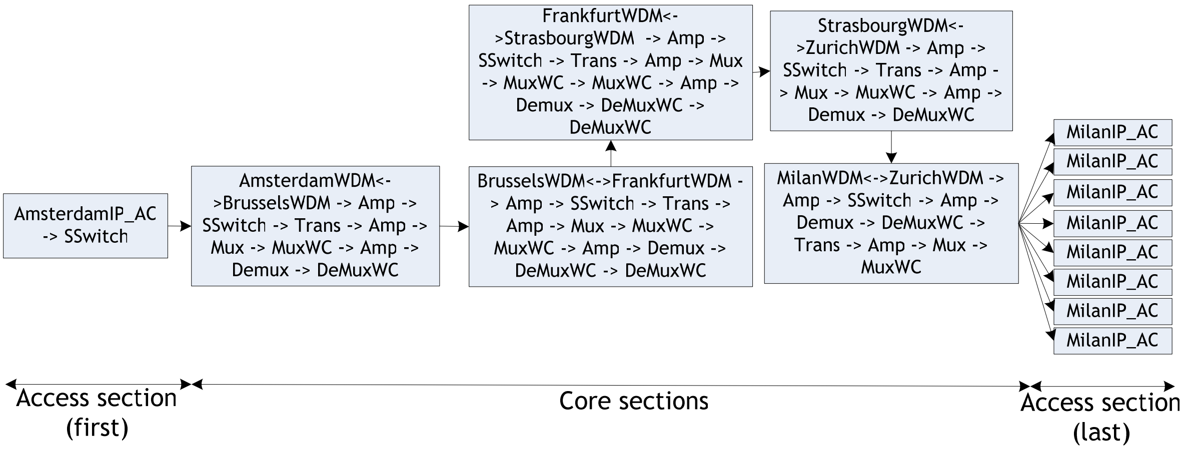


Figure 6.54. – Long demand equipment

The analysis includes no protection case, deflection routing option and series/parallel availability structure variation.

No Protection

Figure 6.55 and Figure 6.56 show component count of the short and long route/demand. Amplifier remains the component with the highest component count, although it has the same percentage as cable in the case of short demand. This is consequence of access sections which make use of one cable. As the core section of the short demand uses only two amplifiers the number of amplifiers and cables is even.

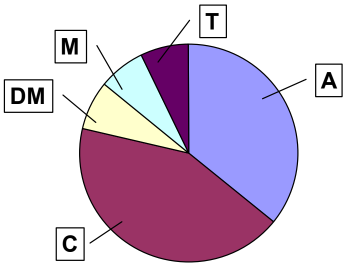


Figure 6.55. – Component count (short, no)

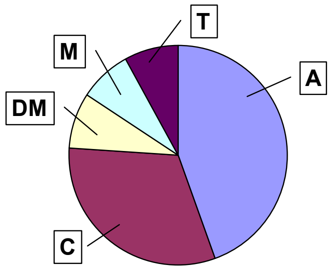


Figure 6.56. – Component count (short, no)

Figure 6.57 depict route/demand unavailability dependence on component type *FR*. Although cable and amplifier share the same component count in the short route/demand, cable has much stronger influence on route/demand unavailability due to length influence on cable *FR*. One should bear in mind the fact that the sharings of the component do not make significant difference as in the OCS case as all the flows in this case use the same fiber, and thus amplifier is shared by the same number of flows as the cable, considering flows of the same demand.

Figure 6.58 show short demand sensitivity on component *FR*, while Figure 6.59 show the same sensitivity of the long demand. The interesting thing is the differentiation of trends belonging to amplifier and multiplexer in short route/demand which melts into the same trend for long route/demand. This is a plain result of different expected unavailability of the rest of the demand which is different is we exclude different components.

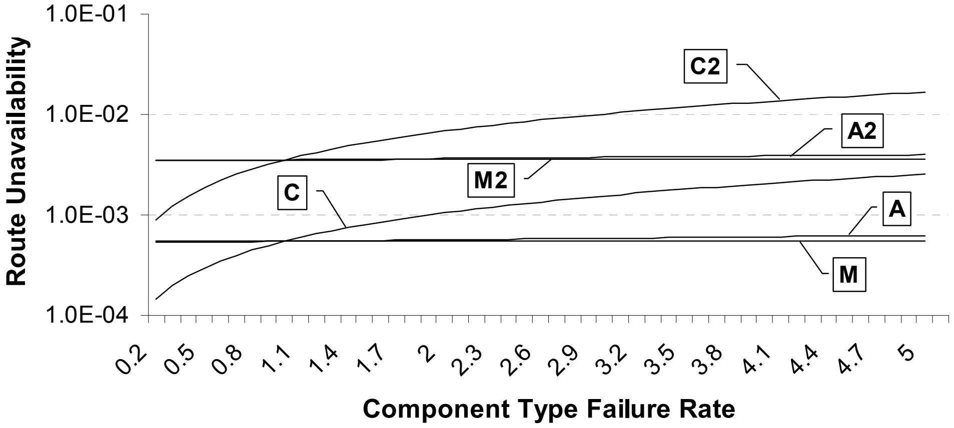


Figure 6.57. – Route/Demand unavailability vs. component type *FR* (no)

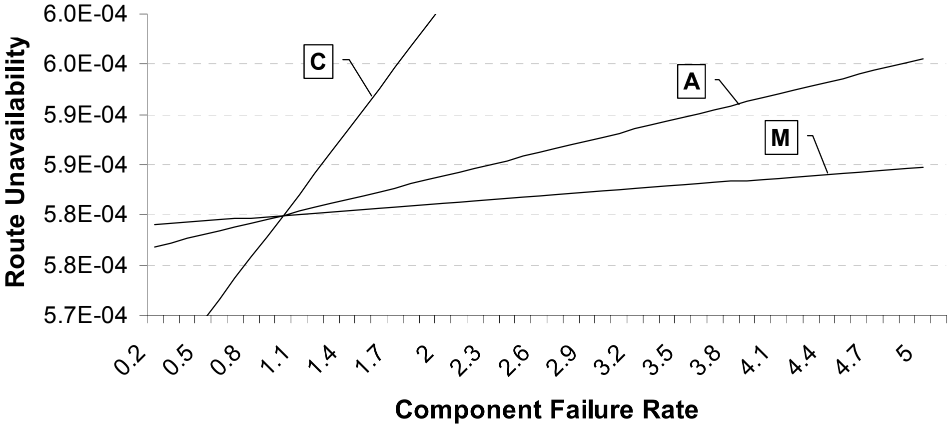


Figure 6.58. – Short route/demand unavailability vs. component *FR* (no)

If the number of components in the rest of the demand is large than this difference will not be too large between different components like in the long demand case. The difference in angle is caused by a relative *FR* scale implying that the same point on *x* axis does not have the same absolute *FR* value on different trends. This causes differences in total unavailability what is resulting in different angles.

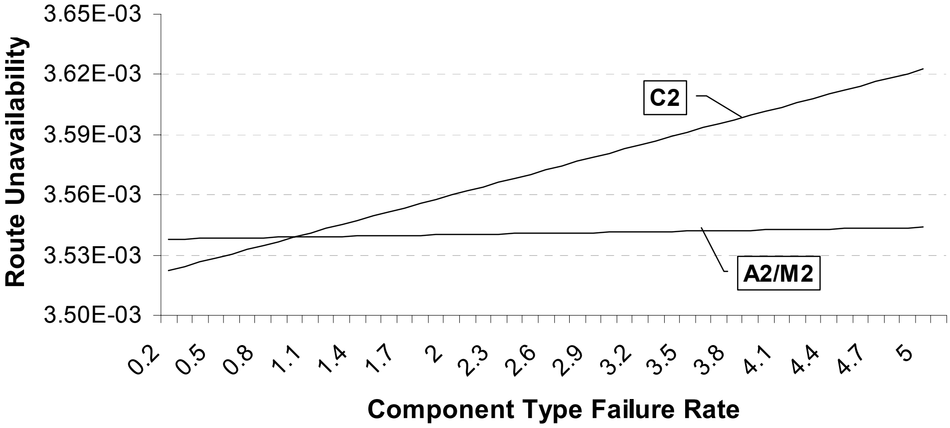


Figure 6.59. – Long route/demand unavailability vs. component *FR* (no)

Deflection Routing

Figure 6.60 and Figure 6.61 depict component count in the case of short and long demand with deflection routing scenario. The choice of demands is the same as in the case of no protection. The percentage of amplifiers is rising confirming that the portion of amplifiers in the total component count increases if the total component count increase. This was clear even from the component count for unprotected large demand.

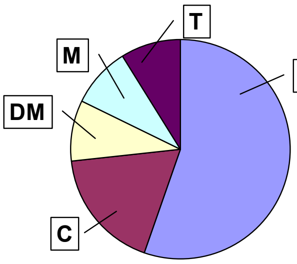


Figure 6.60. – Component count (short, DR)

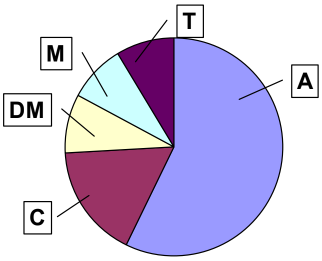


Figure 6.61. – Component count (long, DR)

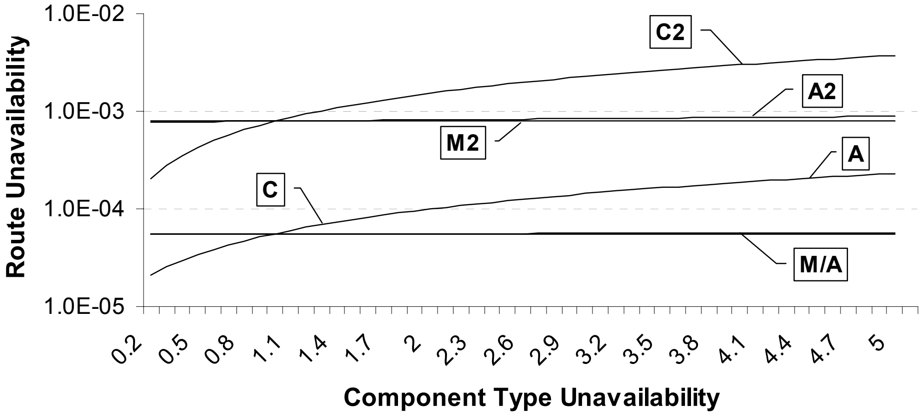


Figure 6.62. – Route/Demand unavailability vs. component type *FR* (DR)

Figure 6.62 shows the route/demand unavailability dependence on component type unavailability. The trends are the same as in the previous cases.

Figure 6.63 and Figure 6.64 confirm the results obtained for the dependence of transport entity unavailability on component *FR*.

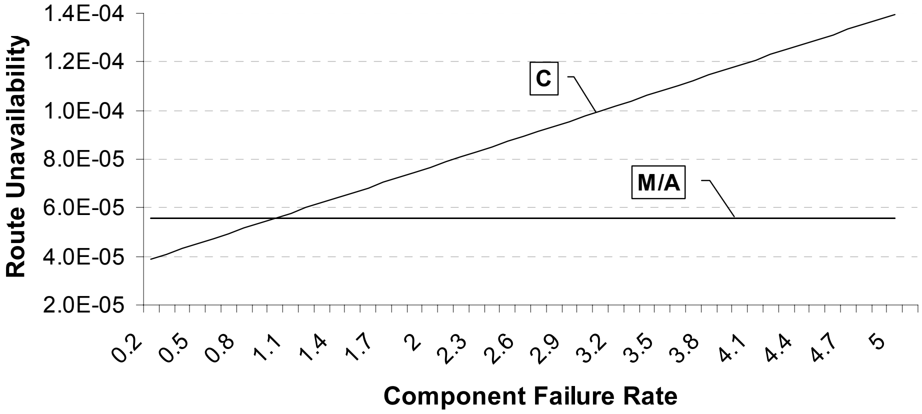


Figure 6.63. – Short route/demand unavailability vs. component *FR* (DR)

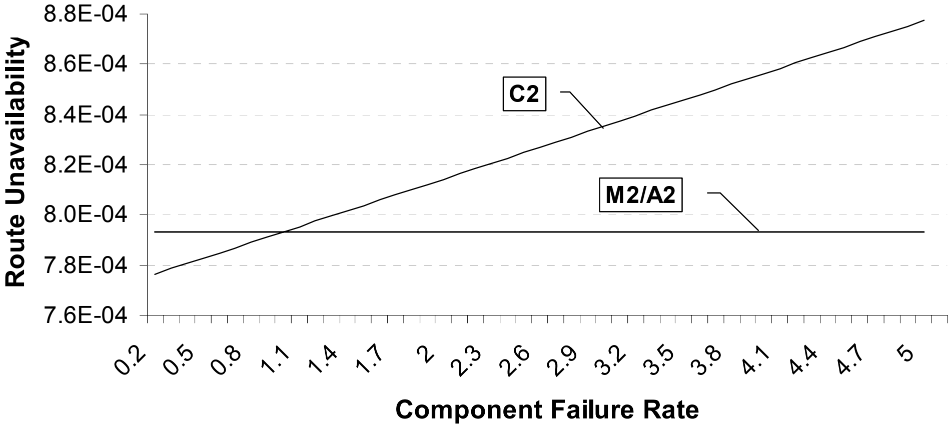


Figure 6.64. – Long route/demand unavailability vs. component Type *FR* (DR)

Series/Parallel

The last analysis on the route/demand level is focused on examining differences between series and parallel demand availability definition as depicted in Figure 6.65. In the series definition demand is a plain series of all flows comprised in sections it uses. Demand will thus be available if all the flows are available. The parallel approach assumes a series of flows parallels. One parallel contains all flows belonging to one section of a demand.

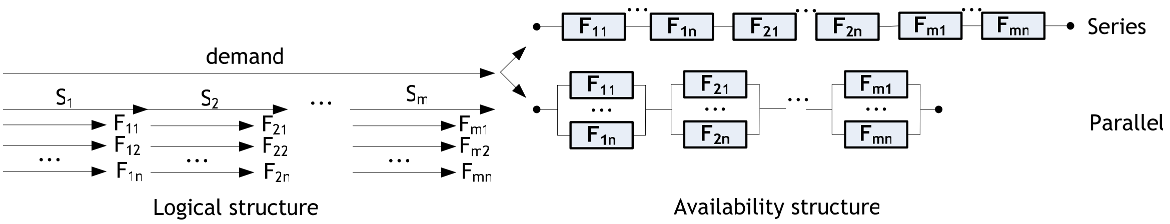


Figure 6.65. – Serial and parallel demand structure

Table 6.10 contains basic information on analyzed demands.

Table 6.10. – Analyzed Demands

Demand	Name	Length [km]	Series	Paralel
Small	AmsterdamIP↔HamburgIP	519	$1.18902 \cdot 10^{-3}$	$1.18902 \cdot 10^{-3}$
Large	AmsterdamIP↔LyonIP	1217	$2.76862 \cdot 10^{-3}$	$2.70100 \cdot 10^{-3}$

The small demand exhibits no difference between series and parallel definition as it contains section with one flow (Figure 6.66). The large demand has several sections with several flows (Figure 6.67).

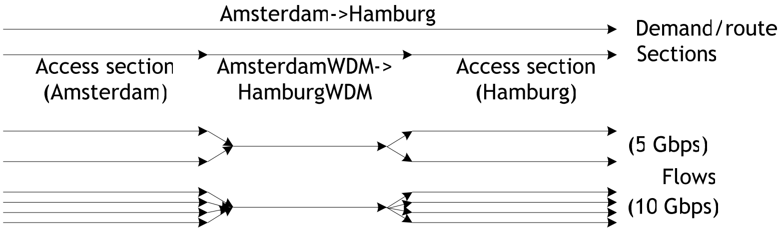


Figure 6.66. – Small demand structure

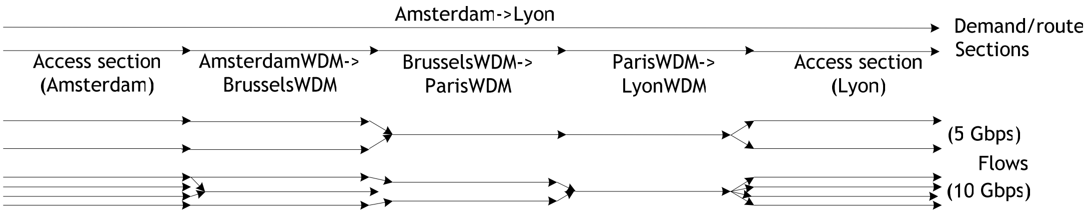


Figure 6.67. – Large demand structure

Figure 6.68 and Figure 6.69 show component count of small and large demand. Amplifier is the dominating component what justifies the assumption that the amplifier component count percentage enlarges with the increase of total component count.

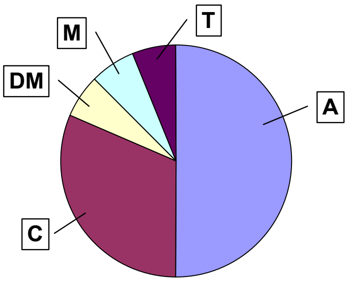


Figure 6.68. – Component count of small demand

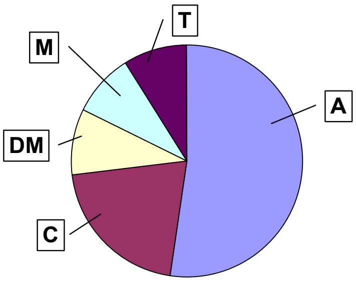


Figure 6.69. – Component count of large demand

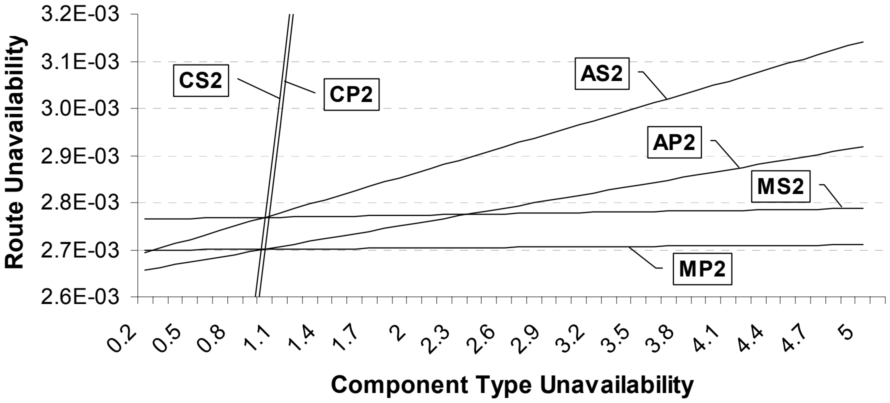


Figure 6.70. – Route/Demand unavailability vs. component type *FR* (5 Gbit/s)

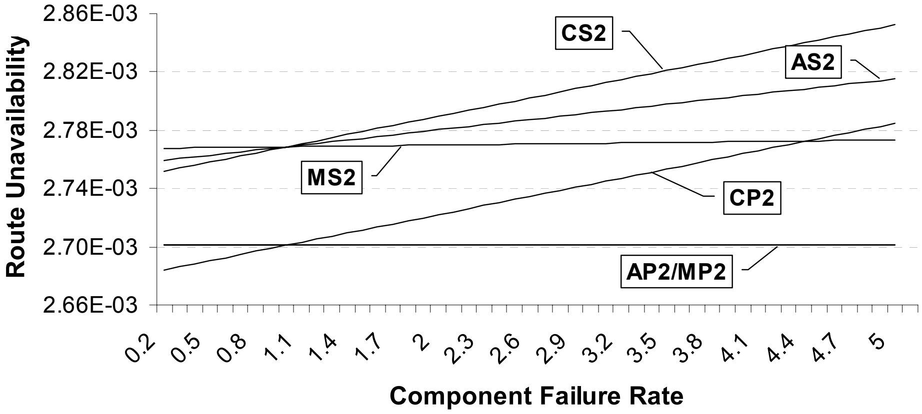


Figure 6.71. – Route/Demand unavailability vs. component *FR* (5 Gbit/s)

Figure 6.70 shows route/demand unavailability dependence on component type *FR*. The network has been dimensioned assuming 2 channel system with homogenous 5 Gbit/s demands between each node pair.

Figure 6.71 shows route/demand unavailability dependence on component *FR* under the same design assumptions as in the previous case.

Network

Figure 6.72 shows network component count. The amplifier is the component with the largest component count.

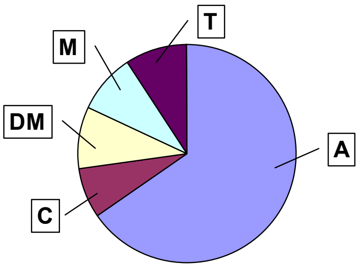


Figure 6.72. – Network component count

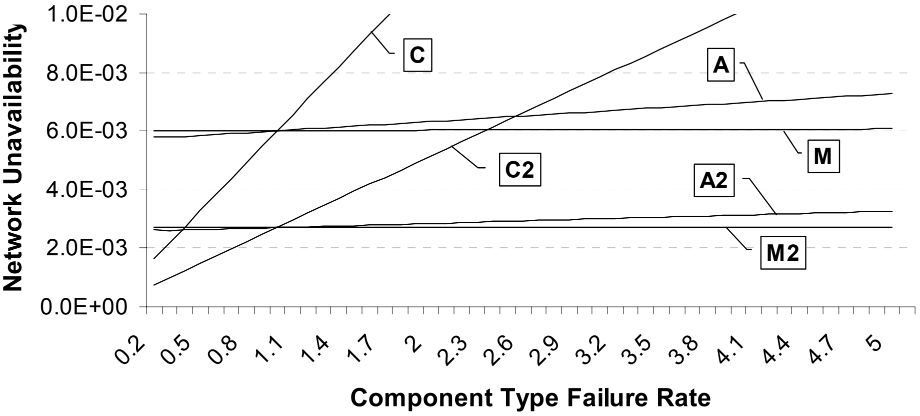


Figure 6.73. – Network unavailability vs. component type *FR*

Figure 6.73 shows dependence of network unavailability on component type *FR*. It is clear that results obtained on lower communication levels (transport entities) emerge on the network level. Cable remains the component with the largest influence on the network unavailability, followed by amplifier and multiplexer. Both worst and mean (denoted with index 2) network unavailability definitions have been addressed. In the worst case network unavailability corresponds to the worst demand unavailability, while in the mean definition case network unavailability corresponds to the demand unavailability mean.

6.4.3. Conclusions

The sensitivity analysis has been conducted on the OCS and OPS paradigms. The goal was to identify critical components for the network unavailability, and parameters that influence that dependency. Cable, multiplexer and amplifier have been taken into analysis.

The circuit switched WDM network was designed without wavelength conversion and optical cross-connects (passive configuration). The analysis included three levels of communication in the network – unidirectional and bidirectional end-to-end between two line cards, and a complete end-to-end communication between two nodes. No protection and 1+1 protection scenarios have been applied to each case. Results include dependence of the transport entity unavailability on the change of a single component *FR*, and on the varying of the component type *FR*. All the components of the same type thus varied their values in the same intervals. This approach shows the influence of component sharing and component count. Cable was the most dominant single component on unavailability as it has been shared by all wavelength paths using fibers in the same cable. Moreover due to unprotected access cable exhibited a strong influence on the logical channel and logical connection unavailability. On the other hand amplifier due to its component count was the component with the strongest influence when component type *FR* was varied.

In the OPS case sensitivity analysis was carried out on all levels of communication ranging from node to node communication (flow and section) to end to end communication (route and demand). The sensitivity analysis was conducted by varying the failure rate of a component in some interval around the expected failure rate level. The obtained results exhibit slightly different trends than in the OCS case. As all the components does not use the same unavailability figures, cable due to the influence of length on the total failure rate becomes a dominant component on all levels of communication. Cable length emphasizes even slight variations in unit length failure rate. On the other hand it has to be taken into account that cable failures have different origin than the failures of the other components. Cable failures are caused by cable cuts, while the other failures are caused by physical impairments of material, or technically related failures. Then the question arises how to reduce the cable failure rate having in mind its strong influence on transport entity and network unavailability. The solution is in reducing the cable cut probability by stronger cable shields or deeper cable lying.

In both cases any kind of protection exhibited reduction of sensitivity of one component or component type on communication availability. This is natural consequence of the fact that only access cables can influence the whole communication on the end to end level. Components with larger number of sharing thus have to be properly protected or avoided what increases the cost of the network.

7.

Conclusion

The objective of the thesis is availability modeling and performance evaluation of the multi-service all-optical network. Optical network architectures have been modeled and analyzed in terms of availability performance. The thesis classifies optical network architectures according to the three paradigms: switching, topological, and protection & restoration. The rest of the chapter summarizes contributions of the thesis.

Classification of protection and restoration schemes, as presented in the thesis, has been made according to the provisioning time of backup transport entity, relative to the service life cycle and to the moment of failure, dedication of the backup transport entity to the working, position of nodes that take switching actions, directionality and action that will be taken once the failure has been resolved.

The thesis proposed the architecture of the multi-service photonic network (MSPN). MSPN provides service classes to clients through switching paradigms. Three fundamental service classes have been identified in the thesis; circuit, packet and burst switched. The architecture reproduces the current architectural state of transport networks, in which fundamental service classes are also provided through switching paradigms.

The MSPN architecture has been presented in terms of layers and their functions, and in terms of generic node structure. Functional description of switching elements and transport interfaces contained within the generic MSPN node has been presented. Relation of the MSPN to the GMPLS has been discussed. Possible ways of encapsulation of the OPS/OBS services in OCS have been presented. OCS can be used to create arbitrary layer topology for the OPS/OBS network. In addition, OCS is used to dynamically distribute transmission resources between switching schemes, at the level of fiber or wavelength channel, depending on the used (required) interface. Optical packet or burst switching are further used to fine-grain the optical bandwidth.

As argued in the thesis, the MSPN architecture allows implementation of any photonic architecture. An application of different topological paradigms has been analyzed. In most cases implementation of topological paradigm requires software that is provided in the network management and control part, and in some cases in additional hardware (for interfacing purposes). Consequently, MSPN nodes can be used to interconnect optical network applying different topological paradigms.

In the context of an evolution from OTN and ASON, the MSPN can be viewed as the next step. Though the MSPN node is a rather complex one, implementation will be possible as soon as the implementation of an OPS or OBS node is possible. The MSPN, through its OCS based interfaces, enables dynamic distribution of transmission resources between different switching paradigms and users/clients. In addition, the structure of the MSPN allows simple addition of other switching paradigms as they might appear.

The chapter on availability modeling presented classification of survivability measures. In general, survivability measures can be classified into three fundamental groups. Topological measures can be used to assess potential ability of a topology to sustain failures. However, protection & restoration scheme precisely defines behavior of the network in the case failure occurs. Time based survivability measures can be used to determine ability of an optical network to quickly restore services affected by the failure. In the thesis we focused on the availability measure, which is defined as a probability that the given entity is non-faulty state. Hence, the definition of availability measure inherently includes network ability to quickly restore failed services.

Generic availability modeling procedure has been presented in the thesis. The procedure takes the model of an optical network and its corresponding transport entities as inputs, and creates availability structure (or graph) for analyzed transport entity. In the next step, generic availability calculation procedures are applied to the availability structure in order to estimate availability performance. In addition to the Monte-Carlo simulation, an application of two analytical procedures has been explained. The first analytical procedure is based on the union of disjoint product terms. The procedure enumerates all paths in the availability structure, yielding union of non-disjoint product terms. The union is then converted into union of disjoint product terms by means of an algorithm.

The second analytical procedure, terminal pair availability, is directly applied to the availability structure. In its essence, the procedures enumerate all of the possible states of an analyzed entity, both non-faulty and faulty. This in turn allows computation of partial availabilities and unavailabilities, and effectively approximate calculation of the availability. The availability structure can be viewed as a compressed expression defining all possibilities for a considered transport entity being in non-faulty state.

Availability structure (or graph) is created from the availability model that defines the relationship between a transport entity and underlying optical components, and/or other lower transport entities. The thesis introduced availability models for optical circuit switching services, for mesh and p-cycle based networks. They differ from the previously published availability models in that they allow accurate availability calculation in case of network resource sharing. On the other hand, the calculation process is more complex. However, in most cases, the error made by not taking into account the network resource sharing into account can be neglected, as the unavailability figures for optical components are low.

Availability modeling procedures described in the thesis differ from other modeling procedures, as described in the availability modeling chapter, in that they are generic, and can be applied to arbitrary level of network detail. In addition, they can take into account complex dependencies between failures of components of an optical network, regardless of whether they are physical or transport entities.

The availability modeling presented in the thesis allows accurate results that can be used in the next step to verify simpler availability models. Simpler models can be in turn used within network design procedures. Availability models and procedures presented in the thesis are part of the integrated object oriented framework for network availability analysis implemented within the Cosmos tool. By keeping the same interface between availability models and procedures, one can apply different and new availability procedures for analysis of the same availability model. The interface between the availability models and availability calculation procedures is availability structure.

Design procedures used in the thesis to create fully defined software model of an optical network are based on the generic heuristic search techniques. Attributable to their inherent characteristics of rather limited requirement of knowledge about the problem being addressed (objective function only) such methods can be quickly applied to a finding of a solution to the design problem. The presented object oriented framework named Nyx is based on two premises. The first one is that general heuristic search techniques require only objective function, and the second one is that they work with the encoded solutions instead of solutions themselves. Therefore, in designing the optimization procedure using Nyx framework, the choice on most appropriate solution encoding should be made first, and followed by the definition of the objective function. The choice of encoding in turn defines allowable generic heuristic search techniques.

The architecture of the Nyx allows for a quick implementation of optimization and design procedures, creation of adaptive optimization procedures, controlled from the objective function, and application and comparison of different heuristic search techniques to the optimization problem.

The thesis presented in detail design procedure for the optical transport networks based on the p-cycle topological paradigm. The design procedure defines two optimization types. In the first (type A), only choice of p-cycles is considered as an optimization variable, while in the second case (type B) both choice of working transport entities, e.g. lightpaths, and choice of p-cycles represents optimization variables. In the availability analysis of the designed network one of the conclusion is that availability of transport entities will be higher if p-cycles are shorter, or if straddling links are used. The latter statement is easily explained by the fact that straddling links divide p-cycle in the best case to half, and in the worst case, protection path for straddling link will be shorter than any protection path for a on-cycle link. Clearly, shorter protection lightpaths will result in higher availability. Finally, by decreasing the length of a p-cycle, one will get the situation in which straddling links are no more possible, due to the fact that p-cycles are minimal in their size. P-cycles effectively become spans, and p-cycle based protection becomes span protection. The final conclusion regarding the p-cycle based networks is that p-cycles actually represent new paradigm that defines rules of resource sharing, in which there is a low level of freedom in the process of determination of the resource sharing.

Availability results presented in the sixth chapter identify two critical optical components; optical cable and optical amplifier. Results also show that by proper application of protection and restoration scheme criticality of components can be reduced. As expected, results confirm that application of a protection and restoration scheme at the lower layer yields better availability performance. This is also expected to be true for time based survivability performances, as the lower layer detects the failure first. Finally, resource sharing, that increases the efficiency of the network design in terms of investment costs, reduces the availability on the other hand.

References

[AA01] M. Lacković, R. Inkret, Network Design, Optimization and Simulation Tool Cosmos, *Proc. Workshop on All-Optical Networks,* WAON 2001, June 13-14, 2001, Zagreb, Croatia, pp. 37-44.

[AA02] M. Lacković, Sensitivity Analysis of Optical Packet Switched Network, requested consulting, March 2004.

[AP01] http://www.carrier1.net, http://ww.ebone.com, http://www.globalcrossing.com, http://www.i-21future.com, http://www.kpnqwest.com, http://www.level3.com, http://www.viatel.com, http://www.colt-telecom.com

[AP02] M. J. O'Mahony, M. C. Sinclair, B. Mikac, Ultra-high Capacity Optical Transmission Networks - European Research Project COST 239, Proc. *Conference on Telecommunications,* ConTEL'93, Zagreb, Croatia, June 1993, *ITA*, Vol. 12, No. 1-3, pp. 33-45.

[AP03] http://www.ep.net/naps_eu.html

[AV01] B. Mikac, R. Inkret, "Availability Model of WDM Optical Networks", *Proc. 2nd International Workshop on the Design of Reliable Communication Networks*, DRCN 2000, Munich, April 9-11, 2000, pp. 80-85.

[AV02] B. Mikac, R. Inkret, F. Tillerot, Wavelength assignment in WDM Networks, - A Comparison of Approaches, in *Optical Networks: Design and Modelling* (G. de Marchis, R. Sabella editors), Kluwer Academic Publishers, 1999, pp. 37-42.

[AV03] R. Inkret, B. Mikac, F. Tillerot, Availability Comparison of WDM Transmission Systems, *Proceedings of TC6 IFIP* 3rd *Working Conference on Optical Network Design and Modelling,* Paris, France, 8-9 February 1999, pp. 405-416.

[AV04] S. De Maesschalck, D. Colle, I. Lievens, M. Pickavet, P. Demeester, C. Mauz, M. Jaeger, R. Inkret, B. Mikac and J. Derkacz, Pan-European Optical Transport Networks: an Availability-based Comparison, *Photonic Network Communications*, May 2003, Vol. 5 (3), pp. 203-225.

[AV05] ITU-T Recommendation E.800 *Terms and definitions related to quality of service and network performance including dependability*, August 1994.

[AV06] R. Inkret, *Algorithms for Calculating Availability of Complex Network Structures*, Internal Report, Dept. of Telecommunications, Faculty of Electrical Engineering and Computing, Zagreb, 2002.

[AV07] W. P. Dotson, J. O. Gobien, A New Analysis Technique for Probabilistic Graphs, *IEEE Trans. on Circuits and Systems*, Vol. CAS-26, October 1979, pp. 855-865.

[AV08] Y. B. Yoo, N. Deo, A Comparison of Algorithms for Terminal Pair Availability, *IEEE Trans. Reliability*, Vol. 37, June 1988, pp. 210-215.

[AV09] W.-J. Ke, S.-D. Wang, Reliability Evaluation for Distributed Computing Networks with Imperfect Nodes, *IEEE Trans. Reliability*, Vol. 46, pp. 342-349, September 1997.

[AV10] D. Torrieri, Calculation of Node-Pair Reliability in Large Networks with Unreliable Nodes, *IEEE Trans. Reliability*, Vol. 43, September 1994, pp. 375-377.

[AV11] A. Iselt, *Ausfallsicherheit und unterbrechungsfreies Ersatzschalten in Kommunikationsnetzen mit Redundanzdomanen*, PhD thesis, 1999.

[AV12] N. Deo, M. Medidi, Parallel Algorithms for Terminal-Pair Reliability, *IEEE Trans. Reliability*, Vol. 41, No. 2, June 1992, pp. 201-209.

[AV13] K. Wood, Factoring Algorithms for Computing K-Terminal Network Reliability, *IEEE Trans. Reliability*, Vol. R-35, No. 3, August 1986, pp. 269-278.

[AV14] V. A. Netes, B. P. Filin, Consideration of Node Failures in Large Networks with Unreliable Nodes, *IEEE Trans. Reliability*, Vol. 45, pp. 127-128, March 1996.

[AV15] R. Inkret, *WDM Based All-Optical Network Modeling*, M.Sc. thesis, (in Croatian), December 1998, Zagreb.

[AV16] H. Hsu, *Theory and Problems of Probability, Random Variables and Random Processes*, Schaum's Outline Series, McGraw-Hill, 1997.

[AV17] A. Papoulis, *Probability, Random Variables and Stochastic Processes*, 3rd edition, McGraw-Hill, 1991.

[AV18] J. A. Abraham, An improved algorithm for network reliability, *IEEE Transactions on Reliability*, Vol. R.28, No. 1, April 1979, pp. 58-61.

[AV19] D. Beichelt, L. Spross, An Improved Abraham-Method for Generating Disjoint Sums, *IEEE Transactions on Reliability*, Vol. R.36, No. 1, April 1987, pp. 70-74.

[AV20] M. O. Locks, A Minimizing Algorithm for Sum of Disjoint Products, *IEEE Transactions on Reliability*, Vol. R.36, No. 4, October 1987, pp. 445-453.

[AV21] J.M. Wilson, An Improved Minimizing Algorithm for Sum of Disjoint Products, *IEEE Transactions on Reliability*, Vol. R.39, No. 1, April 1990, pp. 42-45.

[AV22] M.O. Locks, Note on Disjoint Product Algorithm, *IEEE Transactions on Reliability*, Vol. R.41, No. 1, March 1992, pp. 81-84.

[AV23] L. Wosinska, Reliability Study of Fault-Tolerant Multiwavelength Nonblocking Optical Cross Connect Based on IgGaAsP/InP Laser-Amplifier Gate Switch Arrays, *IEEE Photonics Technology Letters*, Vol. 5, No. 10, October 1993, pp. 1206-1209.

[AV24] L. Wosinska, L. Thylen, Reliability performance of optical cross-connect switches - requirements and practice, Proc. Optical Fiber Communication Conference and Exhibit, *OFC '98*, Technical Digest, February 22-27, 1998, pp. 28-29.

[AV25] RDF93, Recueil de Données de Fiabilité, France Télécom, 1993.

[AV26] B. Mikac, R. Inkret, Availability Comparison of Two All-Optical Network Approaches, *Proceedings of the 1st Working-Conference on Optical Network Design and Modeling* – ONDM'99, Vienna, Austria, February 1997, H.R. van As and A. Jukan (Editors), Chapman & Hall, 1998, pp. 133-146.

[AV27] R. Inkret, B. Mikac, F. Tillerot, Availability Analysis of Different WDM Network Protection Scenarios, *Proceedings on Workshop on All-Optical Networks* - WAON 98, Zagreb, May 6-8, 1998. pp. 121-128.

[AV28] R. Inkret, M. Lacković, B. Mikac, WDM Network Availability Performance Analysis for the COST 266 Case Study Topologies, *Proceedings of the 7th IFIP Working Conference on Optical Network Design & Modelling* – ONDM 2003, February 3-5, 2003, Budapest, Vol. II, pp.1201-1220.

[AV29] ITU-T Recommendation G.911 *Parameters and Calculation Methodologies for Reliability and Availability of Fibre Optic Systems*, April 1997.

[AV30] R. S. Wilkov, Analysis and Design of Reliable Computer Networks, *IEEE Transactions on Communications*, Vol. Com-20, No. 3, June 1972, pp. 660-678.

[AV31] M. L. Shooman, *Probabilistic Reliability: An Engineering Approach*, McGraw-Hill, 1968.

[AV32] M. Lacković, R. Inkret, B. Mikac, An Approach to an IP over WDM Transmission Network Modelling, *Proceedings of 4th International Conference on Transparent Optical Networks* – ICTON 2002, Vol. 1, April 21-25, 2002, Warsaw, Poland, pp. 82-85.

[AV33] D. A. Schupke, Reliability Models of WDM Self-Healing Rings, *Proc. 2nd International Workshop on the Design of Reliable Communication Networks*, DRCN 2000, Munich, Germany, April 9 - 12, 2000.

[AV34] D. A. Schupke, Reliability Models of SDH/SONET Self-Healing Rings over unprotected non-WDM and WDM Networks, *Proc. 8th International Conference on Telecommunication Systems*, Nashville, Tennessee, USA, March 9-12, 2000.

[AV35] D. A. Schupke, Reliability Models of SRP Rings, *Proc. Americas Conference on Information Systems*, AMCIS, Long Beach, CA, USA, August 10 - 13, 2000.

[AV36] J. Lee, Reliability Models of a Class of Self-Healing Rings, *Microelectronics and Reliability*, Vol. 37, No. 8, August 1997, pp. 1179-1183.

[AV37] D. Tsiang, G. Suwala, *The Cisco SRP MAC Layer Protocol*, Internet Draft: draft-tsiang-srp-01, March 2000.

[AV38] M. Jaeger, R. Huelsermann, D. A. Schupke, R. Sedlak, Evaluation of Novel Resilience Schemes in Dynamic Optical Transport Networks, *Proc. SPIE Conference Asia-Pacific Optical and Wireless Communications*, APOC, Shanghai, China, October 14-18, 2002.

[BS01] M. Yoo, C. Qiao, Just-enough-time (JET): A high speed protocol for bursty traffic on optical networks, *Proc. IEEE/LEOS Technologies for a Global Information Infrastructure,* August 1997, pp. 26-27.

[BS02] Y. Xiong, M. Vandenhoute, H. Cankaya, Design and Analysis of optical burst-switched networks, *Proc. SPIE'00 Conference on All Optical Networking: Architecture, Control and Management Issues,* Boston, MA, Vol. 3843, September 1999, pp. 112-119.

[BS03] C. Qiao, M. Yoo, Optical Burst Switching (OBS) – A New Paradigm for an Optical Internet, *Journal of High Speed Networks*, Special Issue on Optical Networks, Vol. 8, No 1, 1999, pp.69-84.

[BS04] I. Baldine, G. N. Rouskas, H. G. Perros, D. Stevenson, Jumpstart: A Just-in-Time Signaling Architecture for WDM Burst-Switching Networks, *IEEE Communications*, Vol. 40, No. 2, February 2002, pp.82-89.

[BS05] J. S. Turner, Terabit burst switching, *Journal of High Speed Networks*, Vol. 8, No. 1, January 1999, pp. 3-16.

[BS06] Y. Xiong, M. Vandenhoute, H.C. Cankaya, Control Architecture in Optical Burst-Switched WDM Networks", *IEEE Journal on Selected Areas in Communications*, Vol. 18, No 10, October 2000, pp. 1838-1851.

[BS07] M. Yang, S. Q. Zheng, D. Verchere, A QoS Supporting Scheduling Algorithm for Optical Burst Switching DWDM Networks, *Proc. GLOBECOM '01*, 2001, pp. 86-91.

[BS08] J. B. Chang, C. S. Park, Efficient Channel-Scheduling in Optical Burst Switching Architecture, *High Performance Switching and Routing, 2002*, Merging Optical and IP Technologies, workshop 2002, pp. 194-198.

[BS09] M. Ljolje, "*Performance Analysis of Transmission Networks with Optical Burst Switching*", (in Croatian) M.Sc. thesis, Zagreb, 2003.

[CM01] ITU-T Recommendation G.8080/Y.1304, *Architecture for the Automatic Switched Optical Network* (ASON).

[CM02] E. Mannie (ed), *Generalized Multi-Protocol Label Switching Architecture*, IETF draft, draft-ietf-ccamp-gmpls-architecture-07.txt, May 2003, expires November 2003.

[CM03] ITU-T Recommendation G.7715, *Architecture and Requirements for Routing the* ASON, June 2002.

[CM04] L. Berger (ed), *Generalized Multi-Protocol Label Switching (GMPLS) Signaling Functional Description*, IETF RFC 3471, January 2003.

[CM05] OIF2000.125.3, *User Network Interface (UNI) 1.0 Signaling Specification*, June 2001.

[CM06] ATM Forum, af-pnni-0055.002, "*Private Network to Network Interface Specification Version 1.1*", April 2002.

[CM07] E. Rosen, A. Viswanathan, R. Callon, *Multiprotocol Label Switching Architecture*, IETF RFC 3031, January 2001.

[CM08] P. Ashwood-Smith, L. Berger (eds), *Generalized Multi-Protocol Label Switching (GMPLS) Signaling Constraint-based Routed Label Distribution Protocol (CR-LDP) Extensions*, IETF RFC 3472, January 2003.

[CM09] L. Berger (ed), *Generalized Multi-Protocol Label Switching (GMPLS) Signaling Resource ReserVation Protocol-Traffic Engineering (RSVP-TE) Extensions*, IETF RFC 3473, January 2003.

[CM10] J. Lang (ed), *Link Management Protocol (LMP)*, IETF draft, draft-ietf-ccamp-lmp-10.txt, October 2003, expires April 2004.

[CM11] H. Smit, T. Li, *IS-IS extensions for Traffic Engineering*, IETF draft, draft-ietf-isis-traffic-05.txt, August 2003, expires February 2004.

[CM12] K. Kompella, Y. Rekhter, *IS-IS Extensions in Support of Generalized Multi-Protocol Label Switching*, IETF draft, draft-ietf-isis-gmpls-extensions-19.txt, October 2003, Expires April 2004.

[CM13] D. Katz, K. Kompella, D. Yeung, *Traffic Engineering (TE) Extensions to OSPF Version 2*, IETF RFC 3630, September 2003.

[CM14] K. Kompella, Y. Rekhter, *OSPF Extensions in Support of Generalized Multi-Protocol Label Switching*, IETF draft, draft-ietf-ccamp-ospf-gmpls-extensions-12.txt, October 2003, expires April 2004.

[CM15] E. Mannie, D. Papadimitriou (eds), *Recovery (Protection and Restoration) Terminology for GMPLS*, IETF draft, draft-ietf-ccamp-gmpls-recovery-terminology-03.txt, January 2004, expires June 2004.

[CM16] J. P. Lang, B. Rajagopalan (eds), *Generalized MPLS Recovery Functional Specification*, draft-ietf-ccamp-gmpls-recovery-functional-01.txt, September 2003, expires March 2004.

[CM17] D. Papadimitriou, E. Mannie (eds), *Analysis of Generalized Multi-Protocol Label Switching (GMPLS)-based Recovery Mechanisms (including Protection and Restoration)*, IETF draft, draft-ietf-ccamp-gmpls-recovery-analysis-02.txt, September 2003, expires March 2004.

[CM18] J. Strand, A. L. Chiu, R. Tkach, Issues for routing in the optical layer, *IEEE Communications Magazine*, Vol. 39, February 2001, pp. 81-87.

[CM19] P. Datta, A. K. Somani, Diverse Routing for Shared Risk Resource Groups (SRRG's) in WDM Optical Networks, submitted in *Journal of Optical Networking* (JON) 2004.

[CO01] I. White, R. Penty, M. Webster, Y. J. Chai, A. Wonfor, S. Shahkooh, Wavelength switching components for future photonic networks, *IEEE Communications*, Vol. 40 , Issue 9, Sep 2002, pp. 74-81.

[DE01] M. Lacković, R. Inkret, B. Mikac, An Object-oriented Approach to Telecommunication Network Modeling, *Proceedings of ESM*, June 3-5, 2002, Darmstadt, Germany.

[DE02] M. Lacković, B. Mikac, Analytical vs. Simulation Approach to Availability Calculation of Circuit Switched Optical Transmission Network, *Proceedings of ConTel*, June 11-13, Zagreb, Croatia, 2003, pp. 743-750.

[DE03] S. Yao, B. Mukherjee, S. J. B. Yoo, S. Dixit, A unified study of contention-resolution schemes in optical packet-switched networks, *IEEE Journal of Lightwave Technology*, Vol. 21, No. 3, March, 2003, pp. 672-683.

[DE04] F. Callegati, W. Cerroni, Wavelength allocation algorithms in optical buffers, *Proc. Of ICC 2001*, Vol. 2 , 11-14 June 2001, pp. 499 -503.

[DE05] F. Callegati, et al., Exploitation of DWDM for Optical Packet Switching with Quality of Service Guarantees, *IEEE Journal On Selected Areas in Communications*, Vol. 20, No. 1, January 2002, pp. 190-201.

[DE06] M. Lacković, R. Inkret, B. Mikac, A Modeling Procedure for IP over WDM Transmission Network, *Proceedings of MIPRO*, May 20-24, 2002, Opatija, Croatia, pp. 45-50.

[DE07] M. Lacković, C. Bungarzeanu, Planning Procedure and Performance Analysis of Packet Switched All-optical Network, *Proc. Conference on Optical Network Design & Modelling*, ONDM 2003, February 3-5, 2003, Budapest, Hungary, pp. 253-271.

[DE08] R. W. Sinnott, "Virtues of the Haversine," Sky and Telescope, Vol. 68, No. 2, 1984, pp. 159.

[DE09] ETSI Recommandation EN 300 416 v1.2.1. *Network Aspects (NA); Availability performance of path elements of international digital paths*, August, 1998.

[DE10] C. Siva Ram Murthy, M. Gurusamy, *WDM Optical Networks: Concepts, Design and Algorithms*, Prentice Hall, 2002.

[DE11] M. Lacković, R. Inkret, Sensitivity Analysis of Component Failures in the Circuit Switched Optical Network, *Proc. 8th IFIP Working Conference on Optical Network Design & Modelling*, ONDM 2004, Gent, Belgium, pp. 205-224.

[DE12] H. T. Mouftah, P.-H. Ho, *Optical Networks; Architecture and Survivability*, Kluwer Academic Publishers, 2003.

[DE13] H. Zang, *WDM Mesh Networks: Management and Survivability*, Kluwer Academic Publishers, 2003.

[GA01] D. B. Johnson, Finding All the Elementary Circuits of a Directed Graph, *SIAM J. Computing*, Vol. 4, No. 1, March 1975, pp. 77-84.

[GA02] E. W. Dijkstra, A Note on Two Problems in Connexion with Graphs, *Numerische Mathematik, 1.* Band, 1959, pp 269-271.

[GA03] J. W. Suurballe, Disjoint Paths in a Network, *Networks*, Vol. 4, 1974, pp. 125-145.

[GA04] J. W. Suurballe, R.E. Tarjan, A Quick Method for Finding Shortest Pairs of Disjoint Paths, *Networks*, Vol. 14, No. 1-4, 1984, pp.325-336.

[GA05] D. Eppstein, Finding the *k* Shortest Paths, 35th *IEEE Symp. Foundations of Comp. Sci.*, Santa Fe, 1994, pp. 154-165.

[GH01] D. E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning,* Reading, Massachusetts, Addison-Wesley, 1989.

[GH02] E. Aarts, J. Korst, *Simulated Annealing and Boltzman Machines*, John Wiley & Sons, 1990.

[GH03] F. Glover, M. Laguna, *Tabu Search*, *Kluwer Academic Publishers*, USA, 1997.

[GN01] R. Inkret, A. Kuchar, B. Mikac (eds.), *Advanced Infrastructure for Photonic Networks: Extended Final Report of COST Action 266*, Faculty of Electrical Engineering and Computing, University of Zagreb, Zagreb, 2003.

[IS01] ITU-T Recommendation G.709/Y.1331, *Interfaces for the Optical Transport Network (OTN)*, February 2001.

[IS02] ITU-T Recommendation G.872, *Architecture for Optical Transport Networks (OTN)*, November 2001.

[IS03] ITU-T Recommendation G.694.1, Spectral grids for WDM applications: DWDM frequency grid, June 2002.

[IW01] S. Dixit (ed), *IP Over WDM: Building the Next Generation Optical Internet*, John Wiley & Sons, 2003.

[IW02] C.Metz, IP Over Optical: From Packets to Photons, *IEEE Internet Computing*, November/December 2000, pp.76-82.

[IW03] Application Note, *Packet-over-SONET/SDH*, Cisco Systems, 1999.

[IW04] White Paper, Cisco's Packet over SONET/SDH (POS) Technology Support; Mission Accomplished, Cisco Systems, 1997.

[OX01] X. Ma, G.-S. Kuo, Optical switching technology comparison: optical MEMS vs. other technologies, *IEEE Communications*, Vol. 41, No. 11, November 2003, pp. S16-S23.

[OX02] P. De Dobbelaere, K. Falta, S. Gloeckner, S. Patra, Digital MEMS for optical switching, *IEEE Communications*, Vol. 40, No. 3, March 2002, pp. 88-95.

[PC01] W. D. Grover, D. Stamatelakis, Cycle-Oriented Distributed Preconfiguration: Ring-Like Speed with Mesh-Like Capacity for Self-Planning Network Restoration, *Proc. International Conference on Communications* (*ICC*), Vol. 1, Atlanta, June 7-11, 1998, pp. 537-543.

[PC02] D. Stamatelakis, W. D. Grover, Theoretical Underpinnings for the Efficiency of Restorable Networks Using Preconfigured Cycles ("p-cycles"), *IEEE Trans. on Communications*, Vol. 48, No. 8, August 2000, pp.1262-1265.

[PC03] D. A. Schupke, C. G. Gruber, A. Autenrieth, Optimal Configuration of p-Cycles in WDM Networks, *Proc. International Conference on Communications* (*ICC*), NYC, April 28-May 2, 2002, pp. 2761-2765.

[PC04] W. D. Grover, D. Stamatelakis, Bridging the ring-mesh dichotomy with p-cycles, *Proc. Design of Reliable Communication Networks* (DRCN), Munich, April 9-12, 2000, pp. 92-104.

[PC05] W. D. Grover, Understanding p-Cycles, Enhanced Rings, and Oriented Cycle Covers, *Proc. 1st International Conference on Optical Communications and Networks*, *ICOCN*'02, November 11-14, 2002, pp. 305-308.

[PC06] W. D. Grover, J. Doucette, M. Clouqueur, D. Leung, D. Stamatelakis, New Options and Insights for Survivable Transport Networks, *IEEE Communications Magazine*, Vol. 40, No. 1, January 2002, pp. 34-41.

[PC07] D. Stamatelakis, W. D. Grover, IP-Layer Restoration and Network Planning Based on Virtual Protection Cycles, *IEEE Journal on Selected Areas in Communications*, (*JSAC*), Vol. 18, No. 10, October 2000, pp.1938-49.

[PC08] C. Mauz, P-cycle Protection in Wavelength Routed Networks, *Proc. 7th Working Conference on Optical Network Design and Modelling,* ONDM'03, February 2003.

[PC09] W. D. Grover, J. Doucette, Advances in Optical Network Design with p-cycles: Joint Optimization and Pre-selection of Candidate p-Cycles, *IEEE/LEOS Summer Topical Meetings 2002: All Optical Networking*, Mont Tremblant, Quebec.

[PS01] S. Yao, B. Mukherjer, S. Dixit, Advances in Photonic Packet Switching: An Overview, *IEEE Communications Magazine*, Vol. 38, No.2, February 2000, pp. 84-94.

[PS02] S. Tucker, W. De Zhong, Photonic Packet Switching: An Overview, *IEEE Communications Magazine*, Vol. E82-B, No. 2, 1999.

[PS03] L. Xu, H. Peros, G. Rouskas, Techniques for Optical Packet Switching and Optical Burst Switching, *IEEE Communications Magazine*, Vol. 39, No. 1, January 2001, pp. 136-142.

[PS04] S. Verma et al., Optical Burst Switching: A Viable Solution for Terabit IP Backbone, *IEEE Network*, Vol. 14, No. 6, November/December 2000, pp. 48-53.

[PS05] M. Lacković, *Performance Analysis of Transmission Networks with Optical Packet Switching*, (in Croatian) M.Sc. thesis, Zagreb, 2004.

[PS06] J. M. Gabriagues, J. B. Jacob, Photonic ATM switching matrix based on wavelength routing, *Proc. Photonics in Switching, pp.2H2*, 1992.

[PS07] J. Benoit, *ATMOS ATM Optical Switching, Project Summary*, Technical Report R2039, EU Project RACE, January 1997.

[PS08] D. Chiaroni, et al., *KEOPS Final Report*: *ACTS Project KEys to Optical Switching AC043*, September 1998.

[PS09] D. K. Hunter, et al., WASPNET: A Wavelength Switched Packet Network, *IEEE Communications Magazine*, Vol. 37, No. 3, 1999, pp. 120-129.

[PS10] L. Dittman et al., The European IST Project DAVID: a Viable Approach towards Optical Packet Switching, accepted for *IEEE Journal on Selected Areas in Communications*, (*JSAC*), 2003.

[RI01] T. H. Wu, *Fiber Network Service Survivability*, Artech House, 1992.

[RR01] J. A. Fee, Method and System for Optical Restoration Tributary Switching in a Fiber Network, U.S. Patent #5,884,017, March 1999.

[RR02] G. Ellinas, A. G. Hailemariam, T. E. Stern, Protection Cycles in Mesh WDM Networks, *IEEE Journal on Selected Areas in Communications*, (*JSAC*), Vol. 18, No. 10, October 2000, pp. 1924-1937.

[SD01] ITU-T Recommendation G.803, *Architecture of transport networks based on the synchronous digital hierarchy (SDH)*, March 2000.

[SR01] D. Zhou, S. Subramaniam, Survivability in Optical Networks, *IEEE Network*, Vol. 14, No. 6, November/December 2000, pp. 16-23.

[SR02] G. Mohan, C. S. R. Murthy, Lightpath Restoration in WDM Optical Networks, *IEEE Network*, Vol. 14, No. 6, November/December 2000, pp. 24-32.

[SR03] A. Fumagalli, L. Valcarenghi, IP Restoration vs. WDM Protection: Is There and Optimal Choice? *IEEE Network*, Vol. 14, No. 6, November/December 2000, pp. 34-41.

[SR04] W. Grover, J. Doucette, M. Clouqueur, D. Leung, D. Stamatelakis, New Options and Insights for Survivable Transport Networks, *IEEE Communications Mag.*, Vol. 40, No. 1, Jan. 2002, pp. 34-41.

[SR05] E. Harrison, A. Farrel, B. Miller, *Protection and Restoration in MPLS Networks: An Examination of the Methods for Protecting MPLS LSPs Against Failures of Network Resources*, White Paper, Data Connection, October 2001.

[SR06] G, Ferraris (ed), *Survivability Strategies with Interactions between Layer Networks*, Project P918, Integration of IP over Optical Networks: Networking Management, Deliverable 5, January 2001.

[SR07] ITU-T Recommendation G.841, *Types and characteristics of SDH network protection architectures*, October 1998.

[SR08] ITU-T Recommendation G.842, *Interworking of SDH network protection architectures*, April 1997.

[TG01] E. Modiano, P.J. Lin, Traffic Grooming in WDM Networks, *IEEE Communications*, Vol. 39, No. 7, July 2001, pp. 124-129.

[TL98] P. Lagasse, P. Demeester, A. Ackaert, W. Van Parys, B. Van Caenegem, M. O'Mahony, K. Stubkjaer, J. Benoit, A. Houghton, K. Fitchew, A. Rawlings, C. De, "Photonic technologies in Europe", published in ACTS Thematic Issue, Published by Telenor AS, R&D, supported by ACTS projects InfoWin AC113 and Horizon AC058, September 1998, pp. 147 pages.

[WS01] X. Cao, V. Anand, C. Qiao, Waveband switching in optical networks, *IEEE Communications*, Vol. 41, No. 4, April 2003, pp. 105-112.

Appendix A – Network topologies

Extensive study of currently deployed pan-European network topologies [AP01][AP02] within the COST 266 action [GN01], resulted in the reference topology suited for a pan-European fibre-optic network. It consists of 28 nodes in major European cities connected by 41 links in a mesh topology (see Figure A.1). The nodes were chosen in such a way that they include some of the European Internet Exchange Points [AP03].

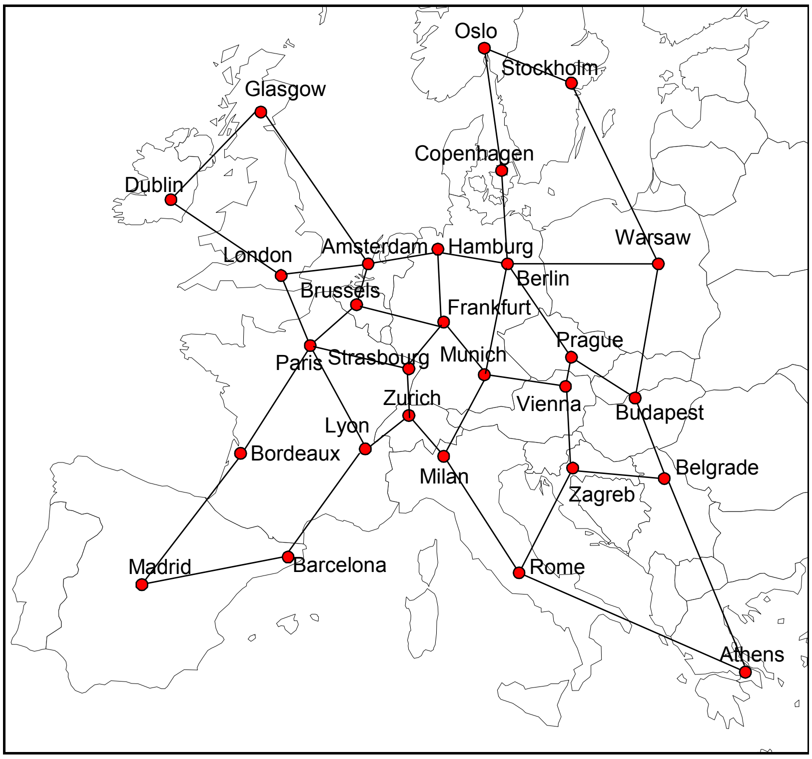


Figure A.1. – Basic reference Topology (BT) for a pan-European fiber-optic network

Starting from this Basic reference Topology (BT) two variations of dimensions are addressed:

- The average node degree, ans
- The number of nodes in the network.

Four topologies have been derived from the BT. The first one is called *Core Topology* (CT) (see Figure A.2), as it only comprises the core part of the BT. The *Large Topology* (LT), illustrated in Figure A.3., on the other hand, is built by extending the BT to more European countries. The CT and the LT contain thus, respectively, less and more nodes than the BT.

The other two derived topologies contain the same nodes as the BT. The difference is in the average node degree of the network, and thus the degree of meshedness. The topology called *Ring Topology* (RT) illustrated in Figure A.4., is a quite sparse one, whereas the *Triangular Topology* (TT) of Figure A.5., is highly meshed. In fact, the last topology is built in such a way that it consists of triangles. Although RT topology is called Ring Topology, the network is a meshed one. It has been called RT, due to the fact that it very much resembles a ring-based network.

Table A.1 and Table A.2 enlist basic parameters for the network topologies.

Table A.1. – Fiber distances for network topologies in *km*

	Mean	**Min**	**Max**
BT	625	218	1500
CT	487	218	783
LT	648	218	1977
RT	630	218	1500
TT	638	218	1500

Table A.2. – Basic parameters for the network topologies

			Node Degree			Node Connectivity			Link Connectivity		
	# Nodes	# Links	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
BT	28	41	2.93	2	5	2.33	2	4	2.46	2	4
CT	16	23	2.88	2	4	2.47	2	4	2.47	2	4
LT	37	57	3.08	2	5	2.44	2	4	2.54	2	4
RT	28	34	2.43	2	4	2.12	2	3	2.15	2	3
TT	28	61	4.36	2	7	2.65	2	5	3.35	2	6

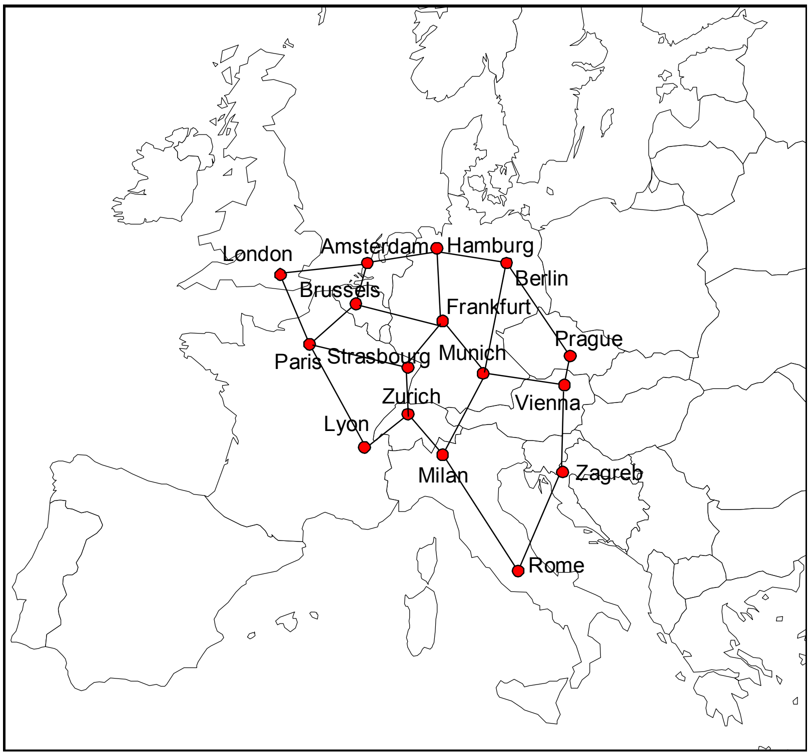


Figure A.2. – Core Topology (CT)

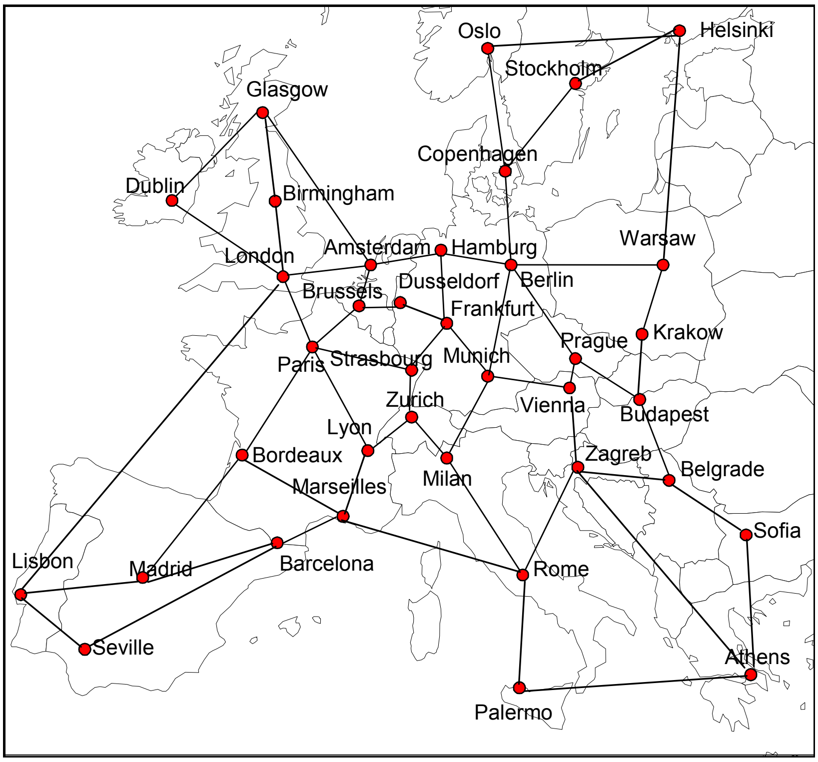


Figure A.3. – Large Topology (LT)

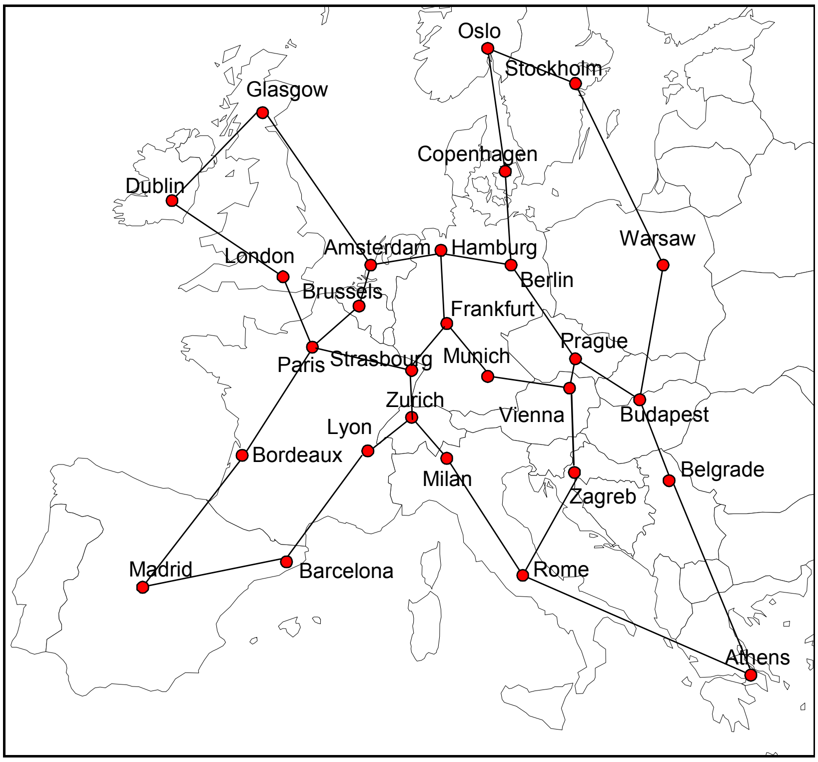


Figure A.4. – Ring Topology (RT)

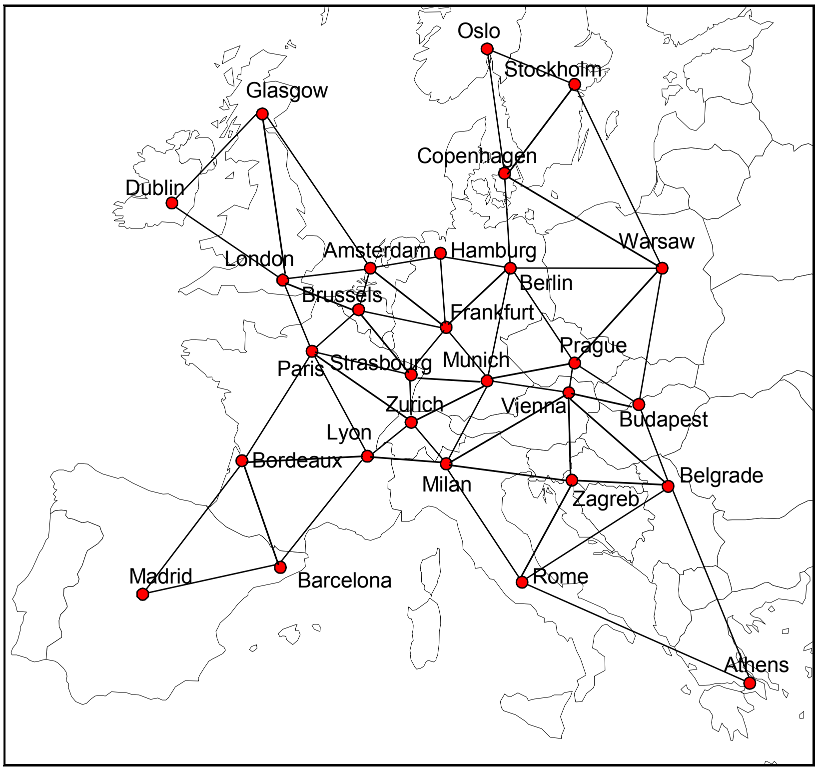


Figure A.5. – Triangular Topology (TT)

Abstract

The objective of the thesis is to analyze optical transport network architectures in terms of their ability to survive failures. Architectures are classified according to three paradigms; switching, topological and protection and restoration. The thesis proposes optical network architecture based on the premise that the provisioning of the fundamental service classes, circuit and packet switched, will be moved to the optical layer. Generic node structure for the proposed optical network architecture is presented with its functional elements and interfaces.

The thesis presents generic availability modeling procedure that consist of modeling of an optical network and its corresponding transport entities, and creating of related availability structure. Further on, availability calculation techniques, analytical and simulation are used to evaluate availability performance. The procedure takes also into account complex dependencies between network entities failures. Availability models for optical circuit and packet switching paradigms are presented.

Design procedures are used to create model of optical transport network. Procedures are based on the application of generic heuristic search techniques, such as Genetic Algorithms, Simulated Annealing and Tabu Search. The thesis describes object orient framework Nyx aimed at fast creation of design and optimization procedures. The thesis presents in detail an application of the Nyx to the design of a network employing p-cycle topological paradigm.

The presented availability modeling procedures are applied in the availability analysis. COST 266 case study topologies are used. Results for the optical circuit switched, mesh and p-cycle, and packet switched architectures are presented. Sensitivity analysis of the availability for the circuit and packet switched architectures is performed.

Keywords

all-optical network, photonic network, availability, p-cycle, network design, heuristic search techniques, sensitivity analysis

Sažetak

U disertaciji su analizirane arhitekture optičkih transportnih mreža s ciljem mogućnosti njihova preživljavanja u slučaju kvara. Arhitekture se klasificiraju prema tri paradigme; prospajanje, topologija, te zaštita i obnavljanje. Predlaže se arhitektura optičke mreže zasnovana na pretpostavci da će pružanje osnovnih klasa usluga komutacije kanala i paketa migrirati u optički sloj. Opisana je generička struktura čvora za predloženu arhitekturu optičke mreže s funkcijskim elementima i sučeljima.

Opisuje se generički postupak modeliranja raspoloživosti koji se sastoji od modeliranja optičke mreže i odgovarajućih transportnih entiteta, te kreiranja pripadne strukture raspoloživosti. U sljedećem se koraku koriste analitičke i simulacijske tehnike za proračun raspoloživosti. Postupak uzima u obzir složene zavisnosti između kvarova mrežnih entiteta. Opisani su modeli raspoloživosti za paradigme optičke komutacije kanala i paketa.

Postupci za oblikovanje programskog modela optičke prijenosne mreže zasnovani su na primjeni općenitih heurističkih tehnika pretraživanja, poput genetičkih algoritama, simuliranog taljenja, odnosno tabu pretraživanja. Opisuje se objektno orijentirano okruženje Nyx, namijenjeno brzom stvaranju postupaka oblikovanja i optimizacije. Detaljno se opisuje primjena Nyx-a na problem optimalnog oblikovanja optičke mreže s „p-cycle“ topološkom paradigmom.

Predstavljeni postupci modeliranja raspoloživosti primijenjeni su u analizi raspoloživosti mrežnih topologija razvijenih unutar projekta Europske Unije COST 266. Prikazani su rezultati analize za arhitekture s komutacijom kanala, „mesh“ i „p-cycle“, te arhitekture s optičkom komutacijom paketa. Provedena je analiza raspoloživosti na primjerima optičkih mreža s komutacijom kanala i paketa.

Ključne riječi

sveoptička mreža, fotonička mreža, raspoloživost, p-cycle, oblikovanje mreža, heurističke tehnike pretraživanja, analiza osjetljivosti

Biography

I was born on December 30, 1972 in Zagreb. Following the high school graduation in 1991, with the work titled “Digital Multiplex System DT-30”, I have started the undergraduate study at the Faculty of Electrical Engineering and Computing, University of Zagreb. I have received the B.Sc. and M.Sc. degrees in electrical engineering with a major in telecommunications from the same faculty in 1995 and 1998 respectively. The topics of the B.Sc. and M.Sc. theses were “Application of Genetic Algorithm to the All-Optical Network Availability Optimization” and “Design of All-Optical Transport Network Based on Wavelength Multiplexing” respectively. From 1996 I am with the Department of Telecommunications, Faculty of Electrical Engineering, University of Zagreb, as a teaching assistant. On three occasions, in 1997, 1998 and 2000, I was working with the France Telecom, Research and Development unit, as an external researcher in the fields of optical network design and availability analysis, and IP over WDM. I have participated in the European Union projects COST 239 "Ultra-High Capacity Optical Transmission Networks" (1996-1999) and COST 266 "Advanced Infrastructure for Photonic Networks" (2000-2003). Currently, as a researcher, I am participating in the EU FP-6 project e-Photon/ONe. My current research interests include availability analysis, optical transport networks, general heuristic search techniques and object oriented analysis and design. I have authored and co-authored more than 20 papers in the international conferences and journals, edited 2 books and 2 international conference proceedings.

Životopis

Rođen sam 30. prosinca 1972. u Zagrebu. Nakon završene srednje škole, s radom pod nazivom „Digitalni Multipleksni Sustav DT-30“, 1991. godine sam počeo dodiplomski studij na Fakultetu elektrotehnike i računarstva Sveučilišta u Zagrebu. Diplomirao sam 1995. godine s temom „Primjena genetičkog algoritma u optimizaciji raspoloživosti sve-optičke prijenosne mreže“. Znanstveni stupanj magistra znanosti iz područja tehničkih znanosti, polje Elektrotehnika, smjer Telekomunikacije i informatika stekao sam 1998. godine, s temom „Oblikovanje sveoptičke prijenosne mreže na bazi valnog multipleksa“. Od siječnja 1996. godine zaposlen sam kao asistent na Zavodu za telekomunikacije Fakulteta elektrotehnike i računarstva u Zagrebu. U tri navrata, 1997., 1998. i 2000. godine, radio sam kao vanjski istraživač u centru za razvoj i istraživanje Francuskih telekomunikacija, na područjima oblikovanja i analize optičkih mreža, te prijenosa IP datagrama preko WDM-a. Sudjelovao sam u radu projekata Europske Unije COST 239 „Optičke prijenosne mreže vrlo velikog kapaciteta“ (od 1996. do 1999. godine), te COST 266 „Napredna infrastruktura za fotoničke mreže“ (od 2000. do 2003. godine). Trenutno sam kao istraživač uključen u rad FP6 projekta Europske Unije e-Photon/ONe. Područja moga trenutnog znanstvenog zanimanja su analiza raspoloživosti, optičke prijenosne mreže, heurističke tehnike pretraživanja, te objektno orijentirana analiza i oblikovanje. Autor sam i ko-autor više od 20 znanstvenih radova objavljenih na međunarodnim konferencijama i u časopisima, urednik 2 knjige, te 2 zbornika konferencija s međunarodnom recenzijom.

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