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# PROTECTION AND TRAFFIC ENGINEERING IN MULTILAYER NETWORKS

Collection of Ph.D. Theses
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# 1 On optical networks

During our life we are permanent users of various networks. We use the road system, the railway network as well as computer and telecommunication networks. Links between components of a network are different. The higher the traffic flow between two nodes is, the higher the capacity of the link is. Today, telecommunication network built up from optical components is considered the most promising one, since thereby data transmission of the largest bandwidth may be achieved. It is commonly used in backbone networks.

The essence of optical telecommunication is that information is forwarded by light rather than electrical signals, using fiber as a medium. Enabled by the technology of wavelength-division multiplexing (WDM), a single fiber permits to transmit a number of wavelength-channels [ML01].

The routes reserved in an optical network are referred to as lightpaths (or $\lambda$-paths). The traffic to a lightpath arrives from the electronic layer, but until reaching its target node, it will be transmitted in the optical layer independently from the number of intermediate nodes [CMLF00] [RBS+01]. At the end of a lightpath, traffic demands may be terminated in the electronic layer or traffic may be forwarded on a following lightpath. This may happen even at another wavelength than the arriving lightpath uses. In my model, I don't suppose wavelength conversion or time division multiplexing (TDM) executed in the optical layer, since the components of their implementation still do not provide sufficient flexibility the methods described in my dissertation is based on. The electronic layer handles lightpaths as virtual links.

The optical layer using WDM is located at the most bottom of the optical network architecture, to which an electronic layer of a kind is built on directly (SDH, SONET, ATM, etc.) [Cin03]. Directly above these, the IP layer as source of traffic demands follows in the protocol architecture. To forward its traffic demands, the electronic layer uses a virtual topology defined by the lightpaths in the WDM layer. Traffic demands may be routed via merging a number of lightpaths.

The bandwidths of real traffic demands are typically much more less than the capacity of a wavelength-channel. This is why traffic grooming is commonly used. This means that in the electronic layer, several traffic demands are combined and simultaneously admitted to a selected lightpath [Cin03].

The electronic layer is fully switched, namely it may be configured automatically through a signalling system. This way it is able to demultiplex traffic demands arriving at a given node through the same lightpath, then to remultiplex them according to claim.

The vertical inter-operation between the two layers built on each other may be different based on the (e.g. business) considerations of their operators. For a peer model, the two layers handle each other as a peer, so the exchange of any control information is permitted. On contrary, an overlay model considers the two layers as a server and a client: using a specified interface, they request services from each other, but know nothing about each other. The augmented model may be considered as a compromise between the two models. If the two layers are owned by one service provider, it is possible to control the two layers simultaneously by a common control plane (integrated model) [SC07].

In my dissertation, questions of traffic engineering are dealt with. Traffic engineering means network operations by which a network is able to operate reliably and efficiently with the optimum utilization of resources [VBA+04]. In an Ethernet network, resources mean network capacity in general, but in an optical network, the correct use of optical-electrical converters shall also be attended.

The unified traffic routing approach widens applicability and enables optimization over multiple layers. To handle a number of layers jointly, however, an appropriate protocol and a common control plane is required [HAC+07]. To implement an inter-layer control plane and to extend the protocol due to the multiple layers, it seemed appropriate to upgrade the MPLS protocol. In this way, the Generalized Multiprotocol Label Switching (GMPLS) protocol [BDL+01] was set up and standardized by the IETF.

In the literature, two basically different approaches to serving traffic demands are found. In case of static approach, the nature of the traffic between network nodes is known in advance. As to the dynamic approach, nothing is known in advance about demands. In that case, the task is to place the arriving traffic demand as well as possible from a given point of view in the knowledge of the current network condition [Hua08].

In a WDM network, the problem of traffic grooming in general consists of the following steps or partial tasks (often combined or interchanged)[ZZM05]:

1. Design virtual topology
2. Determine routes for lightpaths
3. Assign wavelengths to lightpaths
4. Route traffic demands along lightpaths

The goal is in general to use the fewest possible optical-electronic converter and to manage traffic by using the fewest wavelength. With such a goal, however, a number of the above steps are NP-complete even by themselves.

In a dynamic case, on-line heuristics are used to solve the task, where it is of utmost importance to find a quick solution beyond the above goals [Hua08].

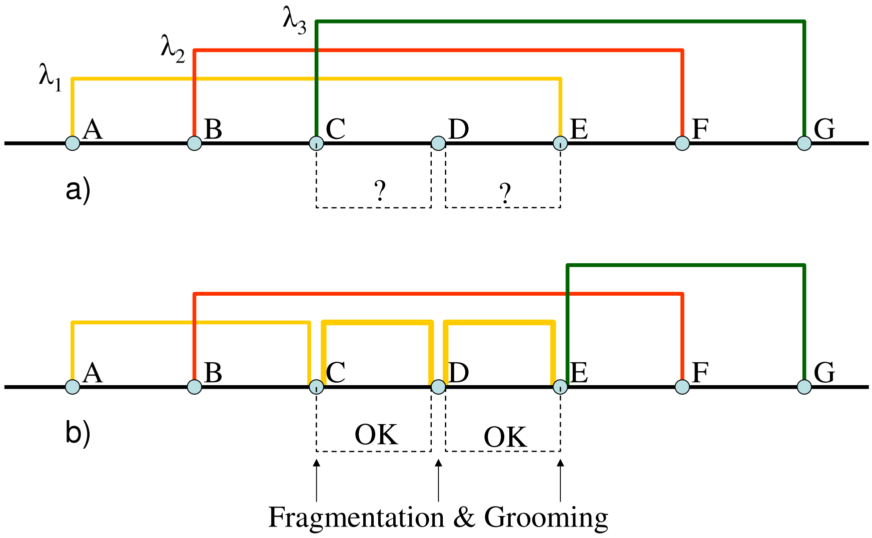



Figure 1: Effect of fragmenting lightpaths: even the last demand can be served

Most dynamic methods are based on special mapping of the optical network, namely modeling it by graphs. Searching for the shortest path on the graph determines in one step the lightpaths to be set up and reserved for traffic demand [ML01] [ZZM03] [OZZ+03] [TBZ+08] [MT08] [CFZ96].

# 2 Motivation

Based on the first few demands set up in a network, certain lightpaths are built up initially. This means that traffic is admitted in the optical layer at the first node of the lightpath, and after passing a number of nodes it will get in the electronic layer again only at the other end of the lightpath. Demands arriving subsequently may be forwarded so that its traffic is multiplexed together with the traffic of lightpaths already existing [ZM02]. Though the arriving demand had not to be rejected, the network is loaded unnecessarily with the bypass possibly generated.

Let's look at the sample network shown in Figure 1/a.

The supposed network consists of seven nodes being able to manage 3 wavelengths each. Let's suppose that as shown in the figure, three demands whose routes use common fibers are active in the network: A–E, B–F and C–G. In this case, all wavelengths of the optical fibers C–D and D–E are reserved, so a demand newly arriving between C–D or D–E could not be forwarded. A C–E demand could be forwarded, but only on the route C–B–A–E, which is a bypass, so unnecessarily needs a significant amount of resources.

Such a problem arising not infrequently may be solved by lightpath fragmentation, where cutting of already existing lightpaths is enabled. In the present case, if the lightpath A–E is cut in the nodes C and D (see Figure 1/b), then on the one hand, the demands C–D and D–E can be served and on the other, the reserved wavelengths may be utilized more efficiently: the traffic of the original lightpath C–G may be delivered in common with the traffic of the original lightpath A–E in a segment.

By using the latest optical solutions, techniques similar to the cutting of lightpath as described above may be applied (e.g. [CZY+06]). Such nodes are referred to as OGT nodes (suitable for Optical Grooming with lightpath Tailoring capability). The faster building up and terminating the lightpaths becomes, the easier releasing an existing lightpath and replacing it with another one becomes.

Via lightpath fragmentation, capacity requirement and blocking ratio will also reduce. Nevertheless, I have not found any source in the literature, which would have scrutinized such utilization of network flexibility, including answers to any question coming up. Through my dissertation, I would like to supply this deficiency.

At the cutting point, the original traffic of the lightpath will get up in the electronic layer. Here, the delivered traffic may be multiplexed with other traffic demands, then readmitted in the optical layer.

The optimum number of the applied lightpath fragmentations is an important question to answer, since while the old lightpaths are released and the new ones are set, traffic may stop even for some seconds. By this, delay or even traffic interruption may be caused. Thus, efforts shall be made to minimize cuttings.

The other extremity is when lightpaths of one-hop length are applied (opaque network [RFD+99]), whereby lightpath fragmentation will be not necessary at all. However, the optical-electronic conversion results in delay ([YL07]), furthermore representing a superfluous load to the electronic layer [MT08]. It can not be disregarded neither that optical-electronic converters are the most expensive parts of the optical nodes. Methods requiring the fewest possible ones of them shall be used [ML01][BBC07][PHS+06][RN07].

If lightpath fragmentation is not applied in a well-thought-out way, traffic demands may have to be rejected due to an increased demand for optical-electronic converters. This is why in my dissertation I pay particular attention to the questions of proper operation.

In the course of my work, I created a node model corresponding to an up-to-date optical router with lightpath fragmenting capability. With a variety of set objectives to be optimized, I have tested its performance in a simulated operating environment and demonstrated the difference between the new and the old model.

Nowadays, quality service is unimaginable without protection. Shared protection is widely used. The flexibility of optical means permits to set up protection routes in the moment of failure. This makes it possible to share optical input and output ports as well as optical-electronic converters. In this way, the demand for protection resources may be reduced significantly. Hereby, it is possible to maintain the same grade of protection at a much lower cost on the one hand and much less demand shall be rejected due to the lack of resources on the other. In spite of any conspicuous benefit of the extended share, I did not meet such an approach in the literature. In this work, I would like to give answers to the questions of this area still unexplored.

# 3 Applied methods

## 3.1 Wavelength graphs

As already mentioned in Chapter 1, most methods developed for dynamic conditions are based on a special purpose-oriented mapping or modeling of the optical network. I myself took such a model, the wavelength graph as a base for my work [CCJ98] [CMLF00] [GMCT03].

In the network, I suppose vertical interlayer operation according to a peer or integrated model, which means that for the two layers, all information about the other layer is available.

Therefore the applied graph model maps over both the physical topology of the network and the resources to be reserved in each network component. Moreover, it is important for the model to carry information about the actual state and settings of network nodes.

The wavelength graph model of a network is derived from the real network topology, the type and actual state of network nodes. Network links are modeled with as many graph edges as the number of managed wavelengths. Nodes are represented in the wavelength graph by subgraphs corresponding to their type.

The most benefit of wavelength graphs is that they contain sufficient information for any shortest path algorithm to find a feasible route to be built up. If edges with different roles are weighted properly, the route of the lowest weight will meet other expectations raised against it. For instance, it will be the shortest possible or composed of the fewest possible lightpaths.

## 3.2 Traffic model and simulation

For dynamic network models, efforts shall be made to achieve the best solution without any previous knowledge of arriving demands. Methods such as those finding an optimum solution by using long calculations in the knowledge of traffic characteristic shall not be applied. To verify my results, I used simulation based methods in the first place.

The generated traffic consisted of demands to be served one after the other, arising according to the Poisson process ordinary in the literature [TBZ+08] [RFD+99]. In my model, traffic demand means a channel of constant bandwidth as a circuit connection a requester needs between a specified source and destination for a period of time defined by him. The distribution of their bandwidth is uniform in a specified range, while that of their holding time is exponential. Traffic demands come up between different node pairs in the network with the same probability.

In the course of simulation, the network is congested and emptied periodically. The more it is saturated, the more demands shall be rejected, however when demands 'participating' in a congestion become lapsed, network resources will get free, blocking ratio will decrease. Therefore, I made simulations to run long enough for the resulting values to represent the tested parameter correctly. Furthermore, I included the middle 95% of the range specified by the fluctuation, in addition to the resulting values.

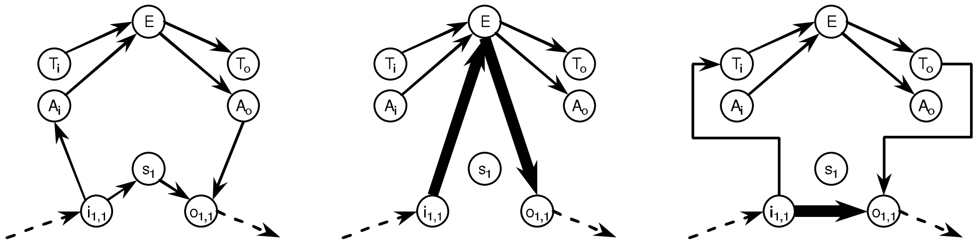
If a demand could be served along the wavelength graph the required resources shall be reserved for that demand. As a demand becomes lapsed the resources used by that demand shall be released. These operations involve wavelength graph modifications according to lightpaths that come to exist or terminate on the one hand and maintaining the associated data structures (such as free capacity, free converters, route of traffic demand) on the other.

# 4 Traffic engineering by lightpath segmentation

**Thesis 1:** ***Network node model with lightpath fragmenting capability***
*[J1] [J2] [C1] [C2] [C3] [C4] [C5] [C6] [C7] [C8] [C9] [C12]*
*I proposed dynamic graph to model optical nodes with lightpath fragmenting capability (OGT) in multilayer GMPLS networks. To serve the demands passing through the nodes I specified an algorithm and weighting functions resulting in routes being the optimum from different points of views. Using simulation method I demonstrated the benefits of applying this model.*

As already described in Chapter 3.1, wavelength graph of the physical network depends on the type of network nodes. Network nodes are represented in the wavelength graph by subgraphs modeling their functions and abilities correctly. The goal is to avoid shortest-path algorithms to find any unfeasible route. From among feasible routes the one should be selected that is optimal from the point of view modeled by the applied weighting function.

In case of an OGT node, the electronic layer makes it possible to demultiplex




(a) Unreserved subports (b) Terminating and departing lightpaths (c) Lgithpath passing through the optical layer – possible to cut

Figure 2: Various states of a fragmenting capable network node

and terminate demands of the arriving lightpaths and to multiplex them again in the lightpaths starting from the node. Likewise, the electronic layer is considered as the source of traffic demand.

Incoming signals shall not be branched, namely the signals coming in at the same port at the same wavelength shall pass on in the same direction alone. This direction shall be the electronic layer or an output port of the same wavelength.

It shall be ensured for the shortest-path algorithm to find a route, which will result in cutting existing lightpaths passing through the optical layer in a node.

Due to this latter requirement, the state of node will vary permanently as a function of the lightpaths just having set.

**Thesis 1.1:** ***Dynamic graph model*** *[J1] [J2] [C1] [C3] [C5]*
*I proposed a graph varying as a function of arriving and terminating demands to model working of OGT nodes. This model contains all the possible vertices and edges of the graph modeling the node as well as a system of rules specifying the valid states of that node. To execute state transition, I specified a lightpath serving algorithm, which will remove and add edges as a function of arriving and terminating demands. It also adjusts the associated data structure.*

In the graph model, I assign a graph vertex to each wavelength of each input and output port. In the following, I will refer to these vertices as subports. Depending on the direction of the lightpath passing through, the subport may be in various states. These are summarized in Figure 2.

For a subgraph representing the OGT node an algorithm is required to execute the appropriate state transitions to present always correctly the lightpaths passing through the subports. It is a requirement for the algorithm to recognize the state of the selected subports. Starting from the recognized state, according to the route selected within the node, the algorithm should modify as necessary the subgraph representing the node and thereby the simulated set of lightpaths. It is unnecessary to modify the graph, if traffic demand may be forwarded through existing lightpaths by multiplexing the traffic of the new demand beyond existing demands of the lightpath. However, the associated data structures (such as capacity, number of spare converters, etc.) should be maintained. The algorithm may be read in Chapter 3.1.3 of the dissertation.

Via a shortest-path algorithm a route may be specified in the wavelength-graph for traffic demands. From the structure and composition of the wavelength-graph specified above, it is always clear that which existing lightpath the specified route will travel along, where a new lightpath shall be set up or the existing one cut to serve the new demand.

Routing is a complex task. Possible routes may be ranked from a number of points of view: for instance based on the number of used lightpaths or the number of involved nodes. The various edges in subgraphs of the nodes may be well assigned to the aspects to be tested, since for instance a separate edge will mark the end of lightpaths or the fragmentation. By an adequate weighting of the edges responsible for the various aspects, it may be achieved for the shortest-path algorithm to specify a route to traffic demand, which is optimum from a given aspect. By using weighting functions, a node model may be adjusted to market demands.

**Thesis 1.2:** ***Weighting*** *[C5] [C9] [C12]*
*I added three weighting functions to the graph model of the OGT node (Subthesis 1.1).*

- *weighting function resulting in the lowest number of hops*
- *weighting function resulting in the route with the lowest number of fragmentation*
- *weighting function resulting in the route passing the electronic layer on the lowest number of occasion*

*Selecting any of the above aspects, any shortest-path algorithm will find an optimum route according to the selected weighting function.*

Supposing 10Gbps links in the COST266 reference network, the average and confidence interval of data of the routes generated on serving demands of 2,900 Mbit/s mean value beside 0% blocking ratio are shown in Table 1. For other topologies and traffic, results are similar. I presented the lengths of routes relative to the shortest paths, while the number of fragmentations are projected to 100 demands.

The benefit of lightpath fragmentation has already been mentioned in Chapter 2: by using it, traffic demands are not driven to by-passes. Routes shorten, network load reduces, whereby the number of demands that may be served increases. However, drawbacks of fragmentation can not be neglected. This derives from stopping the

| Weighting | Pathlength | Lightpaths per route | Converters | Number of cuts |
|---|---|---|---|---|
| shortest path | 108.377%<br>101.35%–115.94% | 3.599<br>3.32–3.87 | 409<br>154–664 | 8<br>1–15 |
| minimal electronic layer usage | 129.945%<br>118.88%–141.00% | 1.42<br>1.30–1.53 | 255<br>104–406 | 49<br>36–62 |
| the least cuts | 131.293%<br>116.96%–145.89% | 3.088<br>2.16–4.01 | 405<br>156–654 | 0.004<br>0–1 |

Table 1: Effect of various weighting on paths

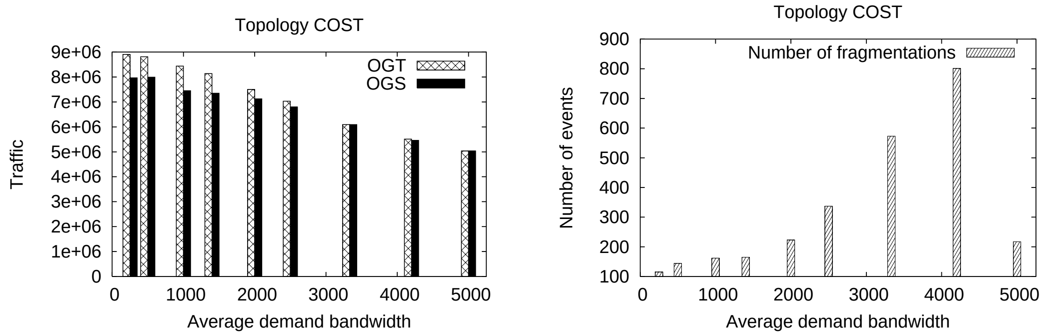
traffic during the execution of lightpath fragmentation. Therefore, it is essential to examine the raison d'ętre for the new model.

**Thesis 1.3:** ***Return of cost*** *[J1] [J2] [C3] [C4] [C5]*
*I proposed a simulation-based method to learn whether with a given topology and traffic characteristic it is worth to switch to a node with lightpath fragmentation capability. The method is based on the cost of lightpath fragmentation and the income from the additional traffic served.*

In Figure 3, results from the simulation run on the COST266 network already described above are shown. Supposing a weighting function that minimizes the number of fragmentations, for traffic demands of various average bandwidth, I performed a simulation to determine the average holding time, for which 1% of the demands arriving at the network will be rejected.

Figure 3/a demonstrates that for traffics of various average bandwidth, how larger traffic a network is able to forward by using a node with lightpath fragmentation capability (OGT) than by using a node without lightpath fragmentation capability (Optical Grooming Simple - OGS). As the average bandwidth of demands increases, so less and less demand may be multiplexed, therefore the difference between the two models disappears gradually.

It is seen from Figure 3/b that during the simulation, how many times lightpath fragmentation was necessary for traffic with various average demand-bandwidth. For demands of low average bandwidth, the rate of multiplexing is high, much traffic demand fits in the lightpaths, therefore the network is fragmented, there is no need for a lot of fragmentation. As the rate of demand bandwidth increases compared to the channel bandwidth, so less and less of them fits in a lightpath. These may be better grouped, need less branches, longer lightpaths may be generated, whereby the number of fragmentation will increase. When the average bandwidth of demands is larger than the half of the wavelength channel capacity (10Gbps), then so few demand may be multiplexed in a lightpath that the number of fragmentations is very




(a) Served traffic (b) Number of fragmentations

Figure 3: Traffic level and number of fragmentations beside 1% of blocking

low. This is why the last column is so low.

For the application of an adaptive optical layer made of nodes with lightpath fragmentation capability, the using of an integrated or peer model is supposed. However, the cost of such adaptivity is a delay resulting from the perpetual modification to the set of lightpaths.

The set of lightpaths is fixed in case of a static or overlay model. However, the price of this is that more network resources shall be reserved and there is an increased traffic loss due to the perpetual change of traffic [C6].

The technology makes it possible to find a middle course between the two extremes.

**Thesis 1.4:** ***Vertical inter-operation between layers*** *[C2] [C6] [C7] [C8]*
*I proposed a hybrid operating strategy giving a novel definition of the vertical inter-operation between the layers of multilayer networks. The strategy combines the benefits from the overlay and integrated interlayer relation models and reduces their drawbacks. Using the overlay model, it works until possible, if however this would involve a loss of traffic, it will change to integrated model.*

In Figures 4 and 5, the loss of traffic and the number of modifications to the set of lightpaths in an 8-wavelength network for the various interlayer relations are shown.

# 5 Shared protection in optical networks

**Thesis 2:** ***Sharing of optical resources*** *[C10] [C11]*
*I proposed to extend the concept of shared protection to share optical-electronic converters as well as optical input and output ports. To realize a cost-effective shared protection and to serve protected demands in case of an OGT node, I proposed weighting functions and algorithms.*

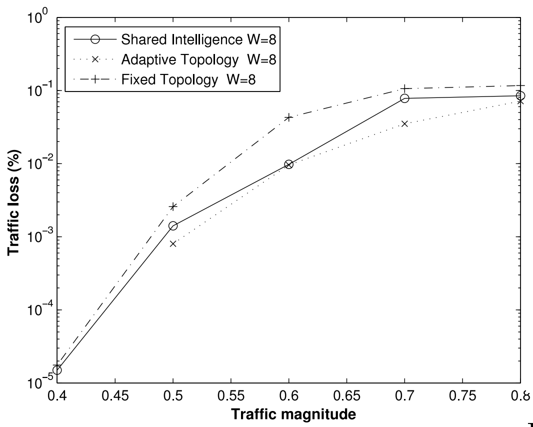



Figure 4: Traffic loss supposing 8 utilized wavelength in case of the three different approaches

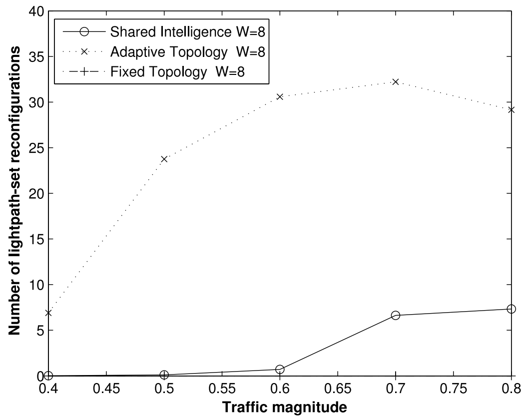



Figure 5: Number of lightpath-set modifications supposing 8 utilized wavelength in case of the three different approaches

Links in a network may be broken off, nodes may break down. A service provider needs protection to provide reliable, fault-tolerant services. In my thesis, I discuss shared route protection of traffic demands. This means that I protect the whole route of a demand rather than a single lightpath. Thus, a protection route as well an active one may pass existing lightpaths, fragment them, or call for a new one. The resources for protection paths may be shared between demands, which do not use common resources in their active paths (shared protection).

One of the most obvious resources to be shared is the capacity to be reserved on the links. However in an optical network, the input and output ports as well as the optical-electronic converters as the most expensive parts of optical nodes, may be shared for protection.

Sharing the subports means that the protection paths passing through them may move on from input subports in various directions within the node at the same time and may enter output subports from various directions within the node. This may be realized so that switching direction of any shared subport will be set only when failure happens affecting protection paths passing through the subport. So subports through which active paths of traffic demands pass can not be shared, since such subports shall not remain unset.

Moreover, directions of the protection paths shall be determined so that irrespective of the place of a single breakdown expected in the network, not more than one direction should be enabled in each subport.

Just as for the active paths, optical-electronic converters are necessary for each protection lightpath, one at the start and one at the end of them. However, it is unnecessary for protection to use as many converters as many protection lightpaths start or end in a given node. On the occurrence of a failure, only a part of the protection lightpath departed or terminated in a node will be activated in most cases. Therefore, just with shared capacity, it is sufficient to reserve only as many converters handling the various wavelengths as maximum required in case of various failures. A precondition of this is that just as with subports, converters shall be set up only when a failure occurs and protection lightpaths to be activated becomes known. This is the sharing of optical-electronic converters.

**Thesis 2.1:** ***Extension of sharing*** *[C10] [C11]*
*I proposed to share the optical-electronic converters and the optical input and output ports in OGT nodes and a method to decide on shareability. The essence of my proposal is as follows: 1) the ports serving protection demands exclusively shall be left open until the occurence of the failure; 2) the maximum number of the optical-electronic converters required for port settings determined by the possible single-failures shall be reserved for shared protection.*

Accordingly, different constraints are relevant to a protection path of traffic demands as to an active path. In case of a subport taking place only in protection paths it is permissible for lightpaths of different direction to pass through it. Therefore the algorithm serving traffic demands shall be modified. It is not sufficient to monitor the state of the graph, but the active resources of passing traffic demands shall also be examined in case of subports taking place only in protection paths. If demands having common active resources are protected in a common subport, while the inner-node direction of their protection paths are different, then their lightpaths shall be cut, the traffic of demands shall be passed through the electronic layer when activating the protection path.

**Thesis 2.2:** ***Extension of lightpath serving algorithm*** *[C10] [C11]*
*I extended the demand serving algorithm proposed in Subthesis 1.1 with steps to be taken in case of shared ports used exclusively for protection. This extension may be considered as the generalization of fragmenting rules. So shared protection becomes applicable on the graph model described in Subthesis 1.1.*

With this subthesis, the algorithms 4.2.1 and 4.2.3 described in dissertation are associated.

In such an algorithm, it is necessary to know the traffic demands using common active resources protected in the given node to avoid the irregular multi-directional activation of lightpaths when common resource fails. Lightpaths of the involved demands will be cut, their traffic will pass the electronic layer of the node. However, it is a difficult task to determine the group of demands concerned in common active resources. Suppose that two demands pass through the investigated subport. In active path of the first one Resource 1 is included, while active path of the second one passes through Resources 1 and 2. If one of them is cut, the other one shall also be cut, since failure of Resource 1 will activate both protection routes. Suppose that the active route of a newly arrived demand uses Resource 2. At this time, lightpaths of all the three traffic demands shall be cut. To review such and more complex cases, a recursive algorithm is needed.

After a demand becoming lapsed, it may be allowed to merge (concatenate) the remained lightpaths. This is required for the number of occupied optical-electronic converters to be as low as possible. In the unprotected case, it was sufficient to examine whether there are pairs of input and output subports that belong to the same wavelength and the lightpaths ending and beginning on them forward the same traffic demands. By permitting multidirectionality, however, this step is more complicated.

**Thesis 2.3:** ***Cutting and merging lightpaths*** *[C10] [C11]*
*I proposed an algorithm to decide on what lightpaths shall be cut and merged in a multi-layer network that employs shared protection when demands are served or disappear. The operation of this algorithm is based on grouping the demands according to their definite direction in the optical layer.*

With this subthesis, the algorithms 4.2.1 and 4.2.3 described in dissertation are associated.

In case of shared protection, network links are generally weighted based on that how many additional capacity shall be reserved to protect the demand along a given path supposing the pre-determined active path. In this way, the route along which the demand may be protected at the least expenditure will be preferred. This view may be generalized and so applicable to minimize the number of necessary optical-electronic converters. The fewest converters shall be reserved for protection consistently with reason, if the fewest possible routes pass the electronic layer. This is why optical-electronic conversion involves a higher cost. Traffic demand however may enter the electronic layer not only if it is routed in that direction, but if due to other demands, individual lightpaths are cut. For this reason, it is requested to avoid fragmentation like in the cases without protection. This is a complicated problem for an optical port transmitting protection paths exclusively, because from the actual topology of a subgraph the fact of fragmentation can not be determined, active resources of passing protection demands shall also be reckoned with. If fragmentation occurs in a subport forwarding protection paths alone, then though one converter remains necessary on the side of cut (either input or output), but as many does on the opposite side as many direction the fragmented routes branch in. So in this case, fragmentations differ from unprotected case in the number of converters necessary to execute them. It is purposeful to route the protection paths through subports forwarding protection lightpaths traveling in the fewest direction involved by common active resources.

| Weighting | Protection: Lightpath length | Protection: Lightpath per demand | Protection: Path length | Protection: Converter number | Network load |
|---|---|---|---|---|---|
| capacity based | 1.235<br>1.072–1.399 | 8.266<br>6.536–9.996 | 9.349<br>8.469–10.229 | 588<br>165–1010 | 8.05%<br>2.345–13.76% |
| inner-node | 1.662<br>1.447-1.877 | 4.464<br>4.003–4.925 | 7.192<br>6.942–7.442 | 113<br>74–152 | 8.885%<br>2.775–14.995% |

Table 2: Effect of weighting preferring port-sharing

## Thesis 2.4: *Weighting*

*I proposed a weighting function to minimize the number of optical-electronic converters reserved for protection. Regarding the generalized rules of fragmentation, this function will prefer paths involving the minimum fragmentation.*

In Table 2 the results of two simulations can be seen. In either of them I used the weighting of Subthesis 2.4, while in the other the weighting function is the generally used one, which minimizes the protection capacity. On applying the currently adopted weighting, the usage of the electronic layer and the number of reserved converters are lower and the set of lightpaths is less fragmented.

For path protection, two disjoint paths shall be assigned to the demand. In the wavelength graph modeling the optical network, however, independence gains a special meaning. The various wavelengths in the wavelength-graph appear as separate edges. When searching for a pair of routes, it may occur that the disjoint paths will pass through the same physical resource, whose failure will involve both routes. Therefore, the wavelength-graph shall be divided in groups of common risk (Shared Risk Group, SRG) [RPS+00] [TR04] [RBS+01]. These are such groups of graph edges that model a physical means (link, network node). The independence of two routes in a wavelength-graph means that they do not pass a common SRG. The procedures used for routing shall be prepared for this.

Suurballe's algorithm [ST84] results in multiple link disjoint paths between the given source and the target node. When searching for the routes, however, the same weighting is used on searching for both routes.

To search for the active and protection paths by using different weighting, it is worth using an algorithm searching for the shortest path. However, since on searching for a route, the optimality of the searched route alone is kept in view, it is not unlikely that the routes so found will cross each other.

| Weighting | Protection | | | | |
|---|---|---|---|---|---|
| | Lightpath | | Path | Converter | Number of |
| | length | per demand | length | number | fragmentations |
| identical | 3.078<br>1.732–4.424 | 3.246<br>2.117–4.375 | 7.158<br>6.81–7.506 | 261<br>109–413 | 149<br>109-190 |
| different | 1.997<br>1.841–2.154 | 3.743<br>3.332–4.154 | 7.252<br>6.883-7.621 | 151<br>80-223 | 34<br>10-58 |

Table 3: Comparation of identical and different weighting of active and protection paths

**Thesis 2.5:** ***Path-pair searching*** *[C10] [C11]*
*I proposed a heuristic to search a pair of active and protection paths in wavelength-graphs, which builds on Dijkstra and Suurballe algorithms well known from the literature. With an iterative call of Dijkstra's algorithm, different weighting may be used to determine active and protection paths. However, the algorithm is greedy, it may not find the pair of routes although it exists in the network. For such cases, I extented Suurballe's algorithm using the same weighting for finding the disjoint pair of paths to be applicable on the wavelength-graph as well.*

The method is demonstrated by the algorithm 4.4.1 of the dissertation. Its essence is that it searches the second route while the weight of the first route's components is strongly increased. If there is a common section of the punished first route and the second route, then the first route will cut the topology in two, while the second will probably not (counterexample may be presented). After removing from the graph the edges contained by the second route's SRGs the found route will be link-disjoint from the route determined in the second place. If after removing the edges, there is no route between the source and target points, the method will try on with the Suurballe's algorithm. For its run a directed graph made of physical elements shall be produced. In such a way the physical elements of the route found by Suurballe's algorithm select a part of the wavelength-graph. In the selected part Dijkstra's algorithm will determine the wavelengths to be used and the node transitions. If the found route is not feasible, then after the temporary removal of responsible elements in the wavelength-graph, the method will start afresh and recur as long as a pair of routes in the reducing graph is found.

In Table 3, comparison between the simulations using various routing processes are shown. If protection and active routes can be weighted in different ways, then protection routes will be fragmented on fewest occasions and fewer optical-electronic converters are needed.

In each of the algorithms I utilized that the active paths of each demand passing the node are known. This is necessary, since without this it could not be established which demands may share resources and which ones may not. However a huge amount of information shall be propagated in the network for this information to be available in updated form in each node. Even if the information is available, it may be of such a huge amount occasionally that calculations will slow down significantly. This problem is not unknown even in the literature. An efficient algorithm named Full Information Restoration (FIR) is presented in [LWKD02].

This algorithm is based on the continuous maintenance of two arrays for each link. In these arrays, values are assigned to other links in the network. This is, however, impossible on wavelength-graphs in such a form. The reason for this is that the presented algorithm is made for such graphs, where a link is modeled by an edge, while for wavelength-graphs, a link is modeled by a group of edges (SRG). This is why failures involve a group of edges rather than the edges themselves. So, the maintained data structure shall be modified accordingly.

**Thesis 2.6:** ***Information propagation***

*I proposed to modify a method of information propagation used for shared protection under the name of Full Information Routing (FIR) known from the literature in order to make it usable in wavelength-graphs too. The basis of this proposed modification is that while the original algorithm supposes the failure of single edges, in multilayer networks, joint failures of edge groups shall be reckoned with.*

# 6 Applicability of results

In a wired communication network, a significant portion of the installation costs is spent to construct the links between nodes. This is why it is essential to make use of the existing links as efficiently as possible. For each of the algorithms, procedures, approaches created in my work, the goal is to better utilize the existing optical network through applying the features of advanced node technologies. Regarding that with lightpath fragmentation, demands may be routed on a shorter path, capacity reserved unnecessarily in a network will reduce significantly to allow forwarding a larger traffic. In my dissertation, I demonstrated how it is worth operating the network, if other resources (e.g. the very expensive optical-electronic converters) are responsible for the bottleneck; saving or other aspects shall be taken into consideration.

In connection with applicability and benefits of the new model, I made a number of investigations. I dealt with network throughput for various traffic and models (e.g. OGS). However during my work, I also experienced that throughput depends on network topology too. In case of the examined aspects, the rate of differences between the results varies rather than the resulting order.

In a network there may exist links connecting two or more major parts of the network. Group of such links is referred to as a bottleneck. The effectiveness of multiplexing is hindered by for example bottlenecks present in the network. It has a great chance to find bottlenecks in a network, if variance of order numbers of the nodes in the graph representing the network is high. This means that there are nodes of high and low order number as well.

During my research, I analyzed the dynamic behavior of the OGT model. Results demonstrated that in case of the OGT model, the rate of fluctuation in blocking due to the dependence from arriving order is much lower than in case of a model unable to fragment lightpaths (OGS). This observation is of utmost importance particularly on design phase, since if traffic is sized with consideration to the highest blocking achieved, then due to the higher fluctuation, forwarding only a lower traffic may be guaranteed in the OGS case.

A network composed of OGT nodes reacts to changes in traffic circumstances much quicker than a network unable to fragment lightpaths. This means that when the traffic level increases, overshot will be smaller and the rate of blocking will be stationary sooner [C5].

By freezing and melting the set of lightpaths, inflexibility of the network directed with the management plane (MP) by an operator may be well simulated. A frosted state corresponds to operating on a fixed set of lightpaths, while a defrosted state to the rare reconfigurations. Expectedly, an inflexible interlayer relation so modeled will react very poorly to a traffic increase, but on its defrosting, blocking will reduce to the blocking level of a flexibly operated network. In an inflexible network, longer routes are resulted, since demands reach their destination mostly through a bypass [C7].

On examining fairness issues, I established that demands of larger bandwidth or more remote end-point nodes are discriminated less in case of the OGT model than in case of the OGS model [C4].

Taking the OGT model as a base, further research has begun. For instance, it has been extended with regard to signal impairment. Also adaptive weighting considering network loads [C9] has been made to it. An algorithm minimizing the number of the applied optical-electronic converters in a mixed network containing OGS and OGT nodes has been constructed [C12].

I summarized my experiences gained from developing the simulator in a design pattern.

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