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EFFICIENT ALGORITHMS FOR MULTI-LAYER UNICAST AND MULTICAST ROUTING IN OPTICAL NETWORKS

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Summary of the Ph.D. Dissertation

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1 Introduction

Efficient routing of unicast and multicast demands in optical networks is a key research area nowadays. The need for communication, including data transfer and human communication, is growing. However, there are open questions that should be solved to improve the performance and the Quality of Service (QoS).

Multicast is cost effective as multiple destinations can be served by a single demand. This may decrease the overall cost and traffic [3]. For various reasons – signalling complexity, lack of good protocols, etc. – it has not spread out yet. Spreading of multicast routing technology promises significant cost and energy saving.

The power requirement of optical networks is growing rapidly. With the extensive growth of the traffic and the number of equipment within the network, this will not be lowered in the near future. As a consequence, it gets even more important to study and apply as many power saving methods as possible. A significant part of the used power is utilized to convert signals between the electric and optical layer of the network. By minimizing the number of these conversions significant amount of power can be saved.

With the amount of data being currently transported the questions of reliability have to be considered seriously. New and efficient methods are needed to provide protection or fast restoration to meet the needed QoS[1] level in case of failure.

Accordingly the dissertation includes methods that provide high availability with the least possible resource utilization, fast restoration in case of link failures and new methods that can be used to capitalize new technological opportunities like physical impairment aware routing technologies, efficient routing of multicast demands, etc.

2 Research Background

The main idea of optical networks was first implemented in the 1960s. From the 1990s optical networks, with the introduction of Wavelength Division Multiplexing (WDM) and other technologies, became the backbone of the world-wide communication. The latest traffic forecasts – [1], etc. – estimate that the amount of transported data will

[1]Here when I talk about QoS I will mostly, but not exclusively, concentrate on the resilience against failures.

reach the zettabyte per year around 2015. Optical networks nowadays are capable of transporting 10-100 Gbit per sec per link per wavelength. Commercially available products will be able to transport around 400 Gbit per sec per wavelength around the mid of this decade [2]. However, the growth of the traffic demand exceeds this trend. Thus, new and more efficient methods are needed for routing and protecting demands in optical networks.

Various solutions have been proposed for both protection [4, 5, 6] and restoration. It was shown many times that it is always better to be prepared for any kind of failure than just react to it when it occurs. The most critical problem with protection methods is that they reserve significant amount of capacity even when it is not needed at all – i.e., before the failure. This leads to the implementation of methods that use a sort of pre-planning in such cases [7].

To minimize the number of conversations an interesting idea of power fine tuning, called Physical Impairment Constraint Routing (*PICR*), was proposed in [8]. The application of this technology to dynamic traffic and to traffic with protection may result in significant power saving. It is always a very important question how to introduce any new technologies in a way that it can co-exist with the current technology in a step by step way. This is also true for *PICR*.

The combination of multicast and *PICR* promises even higher gain.

Nearly all the multicast related problems are known to be NP-hard [9] – i.e., they cannot be solved within 'affordable' time. As a consequence various quasi optimal methods for different multicast related problems were proposed [10, 11], etc. A very interesting quasi optimal methods is called Bacterial Evolutionary Algorithm (*BEA*) [12]. *BEA* mimics the evolution of bacteria. However, according to my knowledge, this method has not been applied to the problems mentioned so far.

3 Research Objectives

The objective of this dissertation is to create new and efficient methods (algorithms) for various kinds of routing problems:

- fast and efficient *restoration of multicast* demands after link failures for cases where no preprocessing is utilized – i.e., the restoration path of the demand should be calculated *'on the fly'*, based on the current state of the network –, including the establishment of new metrics for comparing different solutions,

- cases where the operator is able to define the set of *plausible failures* of the network and has the ability to prepare for *protection* of multicast demands in advance,

- application and extension of well known *heuristics* for the newly proposed *Physical Impairment Constrained Routing (*PICR*) for unicast demands*, solving the routing and the wavelength assignment problems as well. This also includes providing *protection against single link failure* if the network or the application needs it.

- *heuristic and optimal solutions* that solve the problem of *routing of multicast demands* considering *PICR* in case of different network abilities, even with the consideration of wavelength assignment problem,

- application of *BEA* for the routing problem of *multicast and unicast* demands in optical network, considering different network topologies, protection and *PICR* as well.

4 Methodology

The main results of this dissertation were achieved by applying optimal, quasi-optimal and heuristic methods and algorithms to various problems.

I used the Wavelength Graph (*WG*) model, see [13, J2], to represent networks. It allows the modelling of networks with different types of nodes and arbitrary topologies. The *WG* corresponding to the logical network is derived from the physical network, considering the topology and capabilities of physical devices.

I used Integer Linear Program (*ILP*) [14] to find exact solutions to various problems. All the problems I investigated in this dissertation with the use of *ILP* are at least NP-hard, they are related to the Steiner-tree [9] or the multi-commodity flow [15] problem.

In my research, in cases where fast but not always optimal solutions were needed, I applied graph and network flow theory, and complexity analysis to propose new and efficient heuristics. This included cases like routing of unicast demands with and without protection considering physical impairments and restoration of multicast demands. For multicast demands my main interest was the extension of Accumulative Shortest Path (*ASP*) and the Minimum Path Heuristics (*MPH*) [16].

I adopted *BEA* [12, 17] to obtain quasi or nearly optimal solution within polynomial time for unicast and multicast routing problems.

To validate the proposed methods and evaluated their properties a simulation tool was developed using C++, C# and CPLEX.

5 New Results

5.1 Restoration of multicast in grooming capable multi-layer optical networks

TV is still one of the most important media and nearly all the Internet Service Providers (*ISPs*) offer it to their customers. TV stream can be implemented with utilization of multicast. However, as a multicast tree is normally larger in total length than the path of a single unicast demand's route, and the failure of a single link may effect more than one destination it is a key issue to know how to prepare for plausible failure scenarios and how to restore after the failure. Thus, I have investigated the area of routing multicast demands in multilayer, grooming capable optical networks. During these works the used reference and base tool was the *ILP* formulation introduced and co-developed by Marcell Perényi [C1, J1].

Thesis 1 ([C2, C3, J2]). *I have proposed a new exact algorithm and new heuristic algorithms for restoring multicast traffic in multilayer, grooming capable optical networks. I have proposed new metrics that can be used to compare the effects of the restoration time and the cost effectiveness of the obtained solution. Based on the simulation results I have shown that the response time is more important than the restoration cost. To satisfy the need for fast and resource effective restoration technique I have proposed a new method based on pre-planing referred to as Restoration Based on Preplaning created in a restricted network with x method (*RBPx*), where x may refer to any method that can be used to route multicast demands. I have shown that* RBPx *offers fast and resource effective restoration with an affordable off-line calculation need.*

Nowadays an operator can utilize different methods to route a minimal-cost multicast demand, including optimal [18], heuristic [16], and also quasi-optimal solutions [10]. In practice they are all used: optimal and quasi-optimal solutions for static demands, heuristics for dynamic demands. As a consequence restoration technologies should be prepared for all these options.

Thesis 1.1 ([C2, C3]). *I have proposed novel restoration methods for multicast demands for the case of a single link failure. These methods are:*

1. *new heuristic method based on* ASP *that reconnects each of the branches that were pruned away by the failure,*

2. *new* ILP *formulation that provides the cheapest solution for reintegrating target node affected by the failure into the tree without modifying any of the unaffected paths,*

3. *extension of the previously proposed* ILP *formulation that is able to route multicast demands in the failed network even if not all the destinations can be reached.*

I have combined these methods with well-known routing methods – ASP*,* MPH *and* ILP *– into a single simulator, executed exhaustive simulations, evaluated their performance and compared them. I have shown that due to the complexity of the problem in real-time systems the proposed heuristic algorithm, see* 1^{th} *proposition, should be used for restoration.*

To extend *ASP* to partially restore demands – i.e., restore the affected part only – I proposed the following steps:

- A search from both ends of the failed link should be started according to the path of the demand.

- On edges 'before' the failure position – i.e., the ones that are on the side of the source – the capacity reserved for the demand should be released if it was used only to transport data to affected destination(s).

- On edges 'after' the failure position – i.e., the ones that are not on the side of the source –, but before the first destination resources reserved for the demand should be released.

- Find the cheapest path from the source of the multicast to the source nodes of the pruned branches.

To extend the *ILP* for partial reroute case I proposed the following steps:

- free up all the resources exclusively reserved for affected destination nodes of the multicast demand,
- set the cost of the links still used by the demand to zero,
- calculate the optimal solution for a multicast demand that has the same sources as the original one, however its destinations are the affected targets,
- merge this solution into the original one by reserving resources only on edges that were not used to transport data to any of the unaffected destinations.

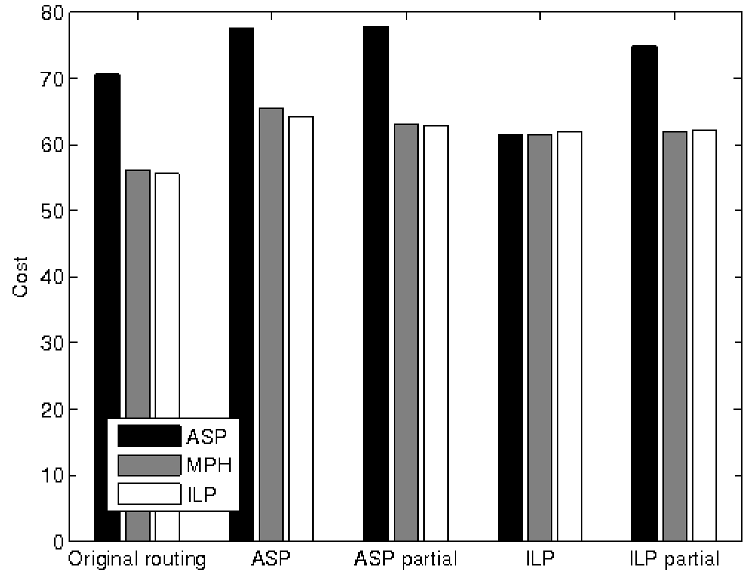
During my simulations I modeled the link failures by temporarily removing the affected link from the network. In these simulations *Cost266BT* [19] and *NFSNet* [20] reference networks were used. Random demands were generated consisting of one 'root' and 5-27 'leaves', all randomly chosen with uniform distribution.

Based on the obtained results, see Figure 1, I concluded that in case of failure the time is the key parameter, thus, the exact and quasi optimal solutions are not affordable.

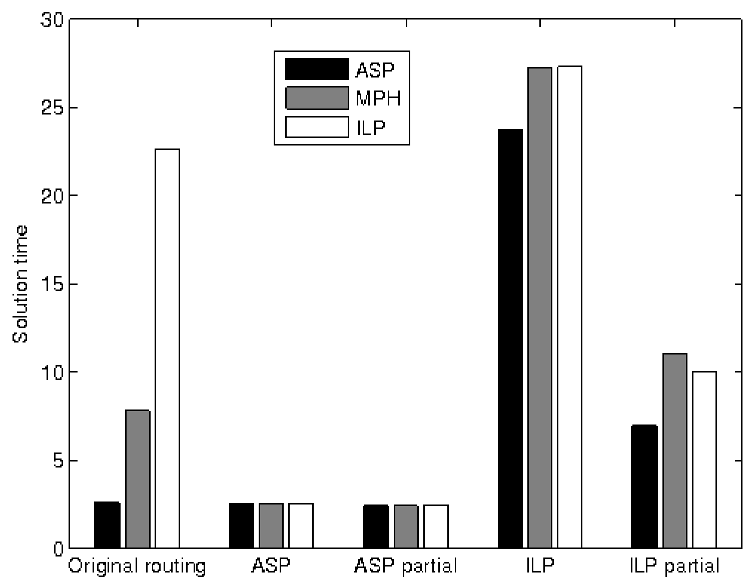
As a response to these recognitions I have started to study the possibility and feasibility of a combined approach that should provide fast response and nearly optimal solution based on calculations done off-line in advance. Restoration based on preplaning is a well known idea in informatics [21, 22, 23]. However, to my knowledge, it has not been applied to restoration of multicast demands in multilayer optical networks.

Thesis 1.2 ([J2]). *I have developed a new combined approach of on-line and off-line calculations for restoring multicast demands for single link failures in multilayer, grooming capable optical networks referred to as* RBPx. RBPx *is based on a new and fast transformation method that is able to transform the routing obtained in the restricted network into the original one considering dynamic traffic. I have proved analytically the optimality of the solutions if a few preconditions hold. For cases where these preconditions do not hold, i.e., the proof is not valid, I have shown the beneficial properties of the method by simulations.*

This approach, to make the off-line calculation less resource demanding, creates a network – so called *restricted network* – in which only a fragment of the wavelengths



(a) Cost of the restored multicast demands



(b) Restoration time

Figure 1: Main properties of the restoration for different optimal and heuristic methods

is presented. In this restricted network, as the number of variables is reduced significantly, the calculation of the restoration path with any optimal method is quite fast – around a few minutes. Thus, it is possible to prepare for most of the plausible link failures. When the failure happens, operator should only search for a previously calculated restoration scenario that fits the current problem and transform it into the original network, considering the possible dynamic traffic, and restore the demand according to it. To support this, I have defined a new parallelism concept and a new parallel searching method.

As rerouting a whole demand may cause *QoS* problem I also investigated the possibility of the idea proposed in Thesis 1.1 – i.e., that the multicast demand may only be partially rerouted.

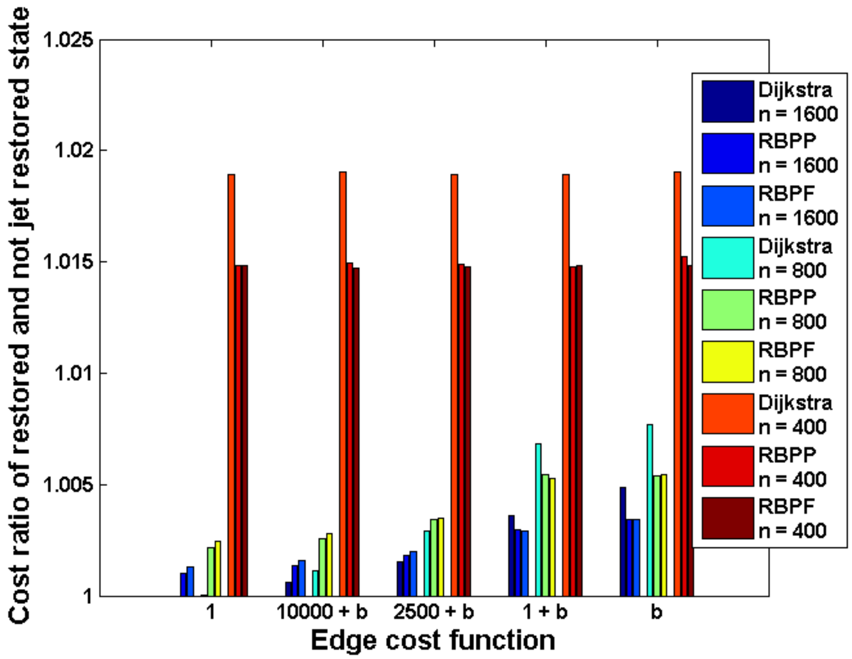
The simulations for this Thesis were done for both the *Cost266BT* and the *Madrid's Core Reference network* [24] by generating 2000 multicast demands with randomly selected node as source and 1 to 27 nodes (in case of Madrid Core Reference network only 1 to 15) as destinations with uniform distribution.

For linear cost functions I have shown, by simulations, see Figure 2, that this approach is cost effective, i.e., its solutions are cheaper than those of the heuristic restoration methods, while in the number of routed demands there is no significant difference. I also showed that *RBPx*'s routing time, in this case the time needed to calculate the path after link failure, is shorter than Dijkstra's, and the needed preparation time is affordable, too.

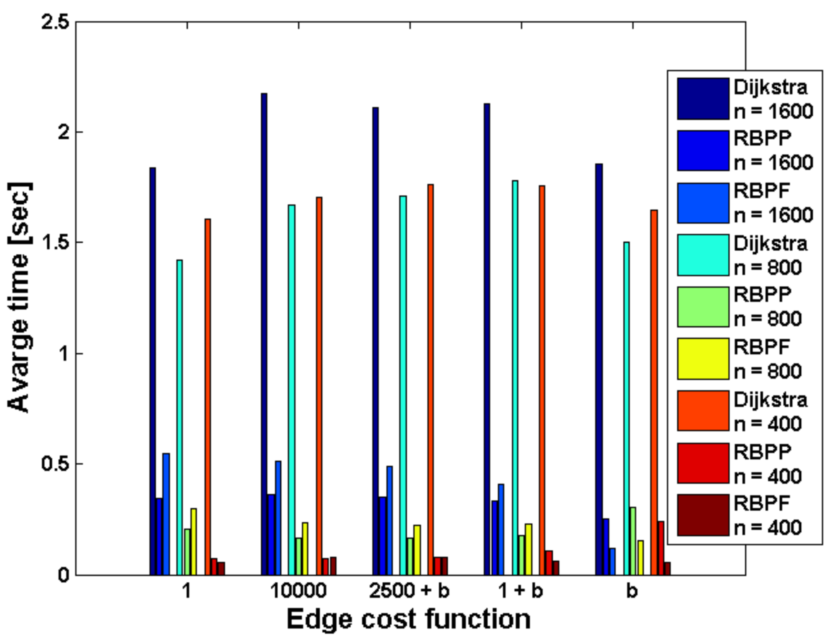
5.2 Physical impairment based routing of unicast demands

New technologies, like the reconfigurable optical add/drop multiplexers (*ROADM*) which provides remote configuration capability, including capacity and power tuning without manual interference for a wide range of wavelengths, help to reduce operational expenditure (*OPEX*). Most of the operators, to maximize their networks performance, also require monitoring and wavelength control functionalities. Thus, additional management functionalities, allowing power measurement and other settings per wavelength, are included in most of the commercial products [25, 26].

Nowadays in nearly all types of *ROADM*s signal power can be tuned with variable optical attenuators (*VOA*) by the management system. In metro *WDM* networks



(a) Ratio of the routing cost before and after the restoration



(b) Restoration time

Figure 2: Main propeties of *RBPx* method

signal power of optical channels is determined by Cross-Phase Modulation (*XPM*) and Raman scattering and not by the Brillouin threshold. This means that the maximum of total power inserted into a fiber is limited not the power used to transfer single demands. Thus, it is suitable to increase the power of some channels up to the Brillouin threshold while other power level of other channels are tuned down to fulfill the *XPM* and Raman scattering constraints. This idea allows the use of Physical Impairment Constrained Routing (*PICR*) for lightpath configuration [8]. In Figure 3 we have two wavelengths: ϕ_1 and ϕ_2. In *Case A* we do not apply *PICR*. Here, due to physical constraints, node A can only reach node C in all-optical way. If there is a demand between node A and D its path can only be established with electric signal regeneration in node B or in C. While *Case B* shows the same case but for *PICR*. Here it is possible to increase the signal power of ϕ_1 to fulfill the Optical Signal-To-Noise Ratio (*OSNR*) request at node D but only if the total power load is affordable on each link. Therefore, it is possible to establish an all-optical connection between A and D.

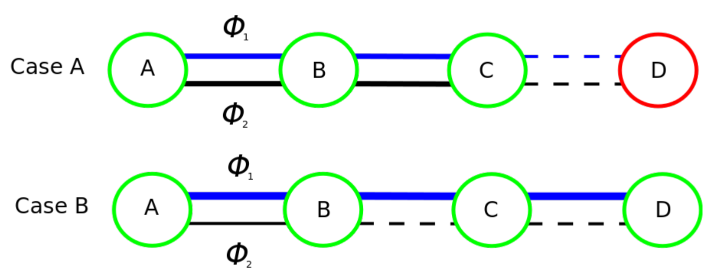


Figure 3: Base idea of *PICR* – thicker line means higher channel power, while broken line denotes lack of data transport

In case of *PICR* maximal distance for a demand is limited by the needed *QoS* and the power constraint of the edges. With the tuning of the signal power, if enough resources are available, most of the routing can be done optically, without electric signal regeneration. Naturally, demands that could not be routed in all-optical way should be regenerated in electrical way somewhere along their paths and routed this way. However, this introduces additional complexity and increases the total power need, which contradicts to green networking aspects. In green networks power consumption should be minimized. Thus, to investigate the benefits, properties and limits of *PICR*

I will not consider any electrical layer related abilities except for the ones that needed to originate and terminate demands in this thesis. More details about this idea can be found in [8, 27].

Thesis 2 ([C4, C5, C6, J3])**.** *I have introduced a new heuristics that can be used to extend any routing method to consider* PICR*. With this heuristics I extended* Dijkstra's *and other algorithms. I applied them for routing dynamic unicast demands with and without protection in multilayer networks concerning physical impairments. With these methods I increased the number of demands that can be routed in all optical way. Based on simulations, I have shown that power sharing may not increase the number of routed demands if protection is needed. During the migration to the* PICR *aware networks, for cases where protection is needed, I proposed a heuristics that increases the number of routed demands by setting up limitations on the ratio of the length of the working to the length of the protection path or the path length of both paths.*

Different methods have been proposed to solve the routing problem in connection with physical impairment awareness. However, in most cases they solve the routing, the wavelength assignment and the physical impairment sub-problems one-by-one or they apply a less generic physical impairment calculation method [28].

Thesis 2.1 ([C4])**.** *I have introduced a new heuristic algorithm to extend* Dijkstra's algorithm *for routing of unicast demands without electric regeneration considering physical impairments. The novelty of this heuristics is its iterative retry and failure approach that increases the number of demands routeable in all optical way.*

The newly proposed algorithm is a 'trial and failure' method that tries to route the demand according to its shortest path. If it is not possible, it detects the edge where a constraint is violated. This link is removed and the search is restarted in the modified network.

Thesis 2.2 ([C4])**.** *I defined edge cost functions for the heuristics proposed in Thesis 2.1 based on the idea of Traffic Engineering (*TE*) to see if any of them minimizes the utilized power or maximizes the number of demands routed. However, based on exhaustive simulations, I have showed that these functions increase the power need and significantly lower the number of routed demands.*

The main idea of *TE* is to choose the path that will interfere less with the future demands [29]. In case of power based *TE* this should mean that feasible path which goes on edges with less previously occupied power is preferable. However, this way *TE* will choose longer paths, that will lead to greater power load on edges. Which will mean even longer paths for the next demands, and so on. At the end the network will be saturated with only a few demands.

Simulation were executed for both *Cost266BT* and *NFSNet* to confirm my theory.

In most cases a single path from the source to the destination can provide the needed availability for the end user. However, there are key services where this is not enough, like international banking or *VPN*s. The first step toward a higher availability is the *1+1* protection [5].

Thesis 2.3 ([C5]). *I have extended the heuristics proposed in Thesis 2.1 for routing demands with protection with and without power sharing. Based on simulation and examples, I have shown that opposed to expectations shared protection may lower the number of routed demands and increase the needed power in large or saturated networks in case of* PICR *when compared to dedicated protection.*

This heuristics incorporates two aspects of the routing: type of protection – i.e., dedicated or shared protection –, and the desire of back-up path – i.e., demands should not be routed without back-up paths or protection is a best effort service. I will refer to the latter case as partial solution.

The simulations were done for *Cost266BT* and *NFSNet*. Random unicast traffic was generated with uniform distribution of the source and destination nodes. The state of the network was periodically monitored, for at least the arrival and termination of 20000 demands.

I have shown that if the system is quite large or the number of demands is significant partial route can be a solution for the operators to maximize their profit and optimize resource utilization.

Migration to any new technology can only be done in a step-by-step manner. This means that the introduction of *PICR* can only be done by reserving a given part of the power and wavelength budget of the operator for this type of routing which will not be enough for all demands in the beginning. Of course during the introduction process the number of demands using this technology should be maximized to speed up the migration process and save as much power as possible. As a consequence a method is needed to filter out demands that should be routed with *PICR* if a path exists for them.

Thesis 2.4 ([C6, J3]). *I have proposed methods to aid the transition from classical networks to networks where* PICR *is used supposing that all the demands have to be protected. These methods filter out the demands that should be routed with* PICR*. The filtering may be based on path lengths or the ratio of path lengths.*

Decision concerning utilization of *PICR* technique should be made between the moment the demand enters the network, and the time just before the bandwidth and power is allocated for it. Limitations can be based on the properties of paths. For *PICR* power usage is the function of the path length. In Thesis 2.2 it was shown that Traffic Engineering does not work for *PICR*. Thus, I decided to use path lengths as the main filtering factor.

The maximum path length is limited in case of *PICR* by default. This length can be obtained based on the properties of the network and the needed level of *QoS*. According to this proposition, operators should not route any demand in all-optical way if the length of its backup or primary path exceeds a given value.

Figure 4 shows the idea behind my second proposition – i.e., the limitation of ratio of the backup and primary paths length. Usually, when finding paths of a demand between distant nodes, the length of a backup path is similar to the length of the primary path. However, this is not true, if end nodes of a demand are located close to each other. In such scenario, backup paths are much longer than the corresponding primary paths. To include these characteristics into my proposal, I introduced another condition: if the ratio of backup and primary path lengths is smaller than a given value, the demand should not be routed with *PICR*.

With the proposed filtering methods I was able to increase the number of routeable demands during the transition to *PICR*. Based on the simulation results path length based filtering outperforms in most cases both the path length ratio-based method and the normal routing. This is achieved by only routing 'short' demands with low power needed. Thus, the number of routable demand is increased by the fact that less power is reserved on each and every link. The power that is saved by this can be used to route other short demands.

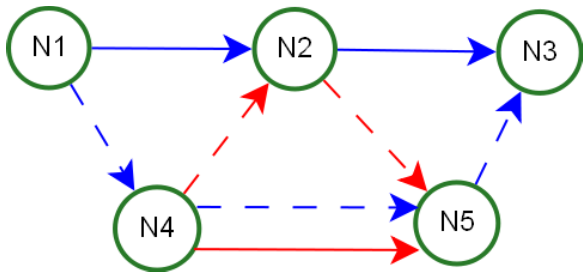


Figure 4: Behaviour of the ratio of the length of the backup path and the primary path. Primary paths are drawn by solid lines, while backup paths by dashed lines. Length of every edge is 1.
Demand $D1$ goes from $N1$ to $N3$. Ratio of the length of the backup and the primary path is 1.5.
Demand $D2$ goes from $N4$ to $N5$. Ratio of the length of the backup and the primary path is 2.

5.3 Physical impairment based routing of multicast demands

The needed bit rate for average HDTV streams, depending on the used encoding, is between 8 and 16 Mbps, which will be increased in the future by the introduction of 3D, 4k and by other new technologies [30] with even higher bandwidth. A TV provider should offer at least 100 to 200 different TV channels to its customers, which is in total more than a few Gbps. This amount of traffic is comparable to the capacity of a wavelength channel. All channels have to be transported from the main site of the provider to all of its clients. Thus, a provider might consider solving this problem by creating a multicast tree in the WDM network from its headquarter to its local bases reserving a full wavelength for the traffic along the full path.

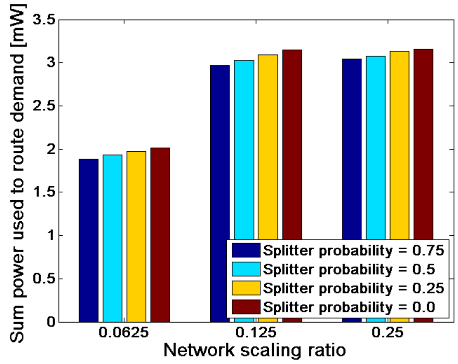
Providers may combine the power of *PICR* with the well known good properties of the multicast to get an easy and cheap service. According to my knowledge, the previously proposed solutions for this problem did not consider all the aspects of routing multicast demands in optical way – i.e., routing, wavelength assignment – or they lacked a generic *PICR* concept. My aim in this thesis was to propose heuristic and optimal solution for the given problem.

Thesis 3 ([C7, J4])**.** *I have proposed two new* ILP *formulations: one to solve the problem of purely optical multicast in multi-layer network in case of physical impairment constraint routing considering optical splitting and one for the case where electric splitting is not limited. I extended* MPH *and* ASP *heuristics to solve the problem of* PICR *where electric splitters are only used in the source and in target nodes. I have shown their beneficial properties by simulation.*

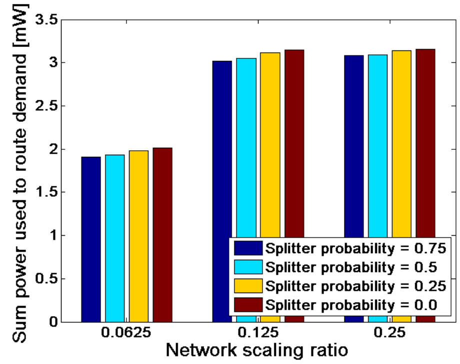
As TV streams are more or less static, it is suitable to calculate their paths in advance in optimal way. New technologies, mentioned in Thesis 2, also offer the possibility to utilize optical splitting combined with optical regenerators and splitting along the path of the destinations. In this case, there are two options: after splitting all the outgoing signals are regenerated to the power that is needed to reach their destination or to the power of the incoming signal. The first one is complicated, but power efficient, while the second is easy to use, but wasteful.

Thesis 3.1 ([J4])**.** *I have proposed two new* ILP *formulations that provides the optimal solutions for routing multicast demands in multi-layer networks, in purely optical way, considering physical impairments. One of these formulations is for networks where optical power cannot be tuned after optical splitting and the other is for those where it is possible. With simulations I have shown the benefits of optical multicast and the option of fine tuning optical powers after optical splitting. With examples, I have also shown why it is important to solve the routing, wavelength assignment and physical impairment problems jointly.*

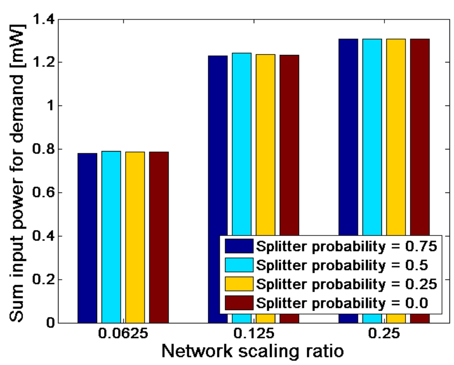
I have incorporated this new *ILP* into my simulator. During the simulations for this Thesis I used *NFSNet Network* and generated multicast demands with 1 to 6 destinations. The nodes where optical splitting was allowed were randomly chosen. I have shown with these simulations that the optical splitting is able to decrease the overall power load of the network by around 3%. The results for fine-tuning of the output signals were not that convincing, but this can be explained with the topology of the used network. Results are shown on Figure 5.



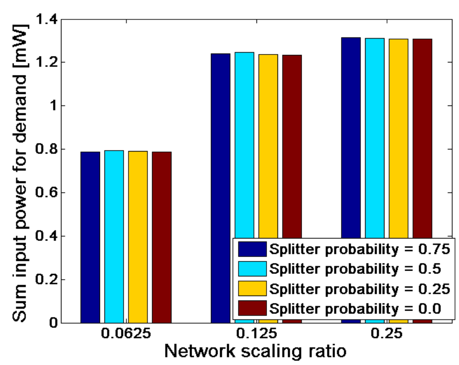
(a) Total power load of the network if output power can be fine tuned for every direction at optical splitters



(b) Total power load of the network if output power cannot be fine tuned for every direction at optical splitters



(c) Total used demand power if output power can be fine tuned for every direction at optical splitters



(d) Total used demand power if output power cannot be fine tuned for every direction at optical splitters

Figure 5: Power needed to route a single demand in average in case of *NFSNet* with different number of optical splitters within the network

Thesis 3.2 ([J4])**.** *I have proposed a new* ILP *formulation for routing multicast demands in optical networks, considering physical impairments and different abilities of the electric layer, i.e., electric splitting and regeneration, while solving the routing and the wavelength assignment problems jointly. This formulation allows the operators to fine the overall optimum for the demands.*

The needed calculation time of the given *ILP*, due to the complexity of the problem and the number of utilized variables, can be problematic if the TV stream is modified time-to-time. Heuristic solutions for the problem of physical impairment aware multicast routing have been proposed by various authors [31, 32], but they did not consider all the aspects of routing.

The optical splitting capability is not yet deployed in every network. For the time being when this new splitting functionality will be widely used an operator may try to route multicast demands in a nearly all optical way, that would mean that electric splitting functionality can be used at source and destination nodes but only for multicast demands, no optical splitting is considered yet.

Thesis 3.3 ([C7, J4])**.** *I have modified* ASP *and* MPH *heuristics for the case of* PICR *when only electric splitting is allowed and only in the source and the target nodes for the given demand in multi-layer optical networks, they will be referred to as* EASP *and* EMPH*, respectively. I have shown that* EMPH *is optimal if only one demand is routed at a time, enough resources are available in case of normal networks*[2]*. I compared their performance to that of Application Level Multicasting (*ALM*) and their none* PICR *aware versions and showed that with my extensions the number of demands routeable is significantly increased.*

ASP, which is more or less a sequentially applied *Dijkstra's algorithm* for every destination, can be easily extended to the given problem in exactly the same way as the normal *Dijkstra* was extended in Thesis 2.1.

However, *MPH* has to be approached with more caution. The problem here is the following: *MPH* selects into the tree the next closest node, which has not been reached yet. However, here we do not know for sure which is the next closest node –

[2]Here 'normal network' means that if two paths are going from the same node to the same destination, than the shorter one goes through less nodes.

it is possible, that its path violates one or more constraints, i.e., it is not usable. One can only say that which is the node with the shortest path candidate. Thus, a list has to be maintained that contains nodes not yet reached, their shortest paths and the edges which cannot be used by the given demand based on the previous steps.

During simulations for this Thesis I used *Cost266BT* where around 2000 scenarios were generated with 1 to 5 multicast demands in each with 1 to 26 destinations selected with uniform distribution. The performed simulations, see Figure 6, showed that the newly proposed methods increase the number of reachable nodes.

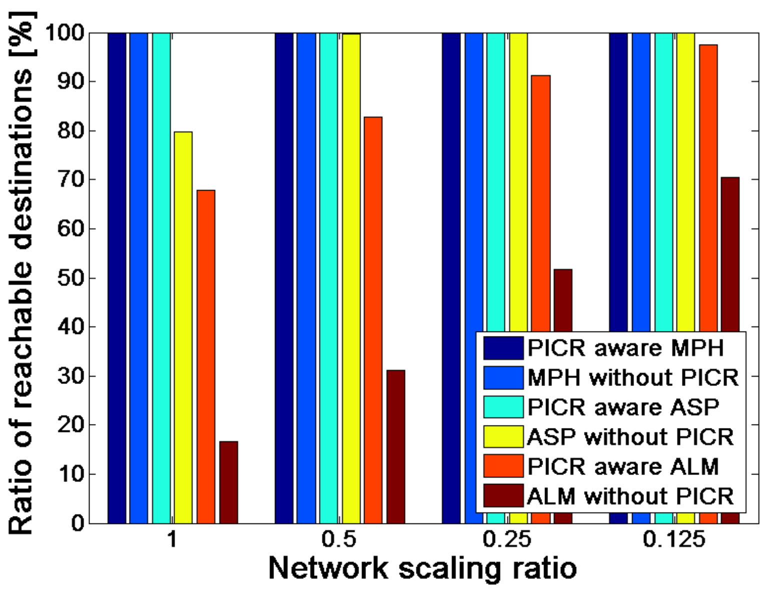


Figure 6: Ratio of the routable demands with the newly proposed algorithms and without it

5.4 Applying Bacterial Evolutionary Algorithm to Routing Problems

The complexity of the problems to be solved is growing. The user's demand to obtain good results within affordable time is getting more and more important. These two demands inspired the spread of soft-computing in nearly every field of informatics.

There are various soft-computing methods that can be used to obtain quasi optimal solution for different problems – Tabu-search [33], Simulated Annealing [34], Neural Networks [35], Fuzzy-systems [36], etc. All these methods have their benefits and drawbacks, their strengths and weaknesses. It is always the decision of the engineer which one of them will be used and – most importantly – how it will be used. These two decisions determine the quality of the obtained results. When a new idea is developed in this field it is always a question which problem can be solved easily with it. One of the newest methods is the Bacterial Evolutionary Algorithm (*BEA*) that was applied to various problems earlier with great success. However, according to my knowledge, this idea has not yet been applied to find the routing path and the wavelength assignment jointly in optical networks.

Thesis 4 ([C8, C9, J4]). *I introduced a new routing framework, based on* BEA*, that allows the operators to find a trade-off between the quality of the solution and the needed time to compute it for nearly every routing problem where at least one edge cost based heuristics exists and a fitness function can be defined. I extended this framework by defining new fitness function and heuristics for routing of unicast and multicast demands, for routing with and without protection and for* PICR *as well.*

In Thesis 2 and Thesis 3 I proposed optimal and heuristic solutions for the routing and restoration of multicast and unicast demands. However, in many cases it is not needed to be as accurate as an *ILP*, just a solution that is good enough is required which should be better than a simple heuristics. Various methods were proposed in the literature for the problem of multicast demand with or without protection, this includes optimal [37], and heuristic methods – in case of protection p-tree [38], dual tree [39], etc. – but meta-heuristic approach for grooming capable multi-layer optical networks is missing. To fill in this gap I proposed a new *BEA* based solutions for the given problem.

Thesis 4.1 ([C8, C9])**.** *I proposed a new coding scheme that can be used to route unicast and multicast demands in multi-layer networks with and without protection with the use of* BEA*. I have introduced a new genotype that consist of a virtual edge cost system and the routing order of the demands. I have also shown analytically that for a set of cost functions this genotype cannot be simplified. By simulations I confirmed the ability of the approach to provide solutions close to the optimal, even optimal for these problems in polynomial time.*

To my knowledge this was the first application of *BEA* for multicast demands in multi-layer, grooming capable networks.

The main idea is as follows: instead of creating a new heuristic method we should somehow create or define the costs and demand orders that allow simple classical plain heuristics to find a quasi optimal solution. This 'good' order and cost are the ones that should be created by *BEA*. In practice this means that I defined the four main *BEA* components, operators – phenotype, genotype, fitness and genotype calculation – as follows:

- Phenotype is the result for the given problem, i.e., the routing of the demands.
- Fitness is the routing cost of the demands, multiplied by minus one.
- Genotype consist of the followings: a virtual cost system, that will be used during routing, and routing order.
- The phenotype is calculated from the genotype by routing demands on a virtual graph where edge cost is equal to the value stored for the given edge in the genotype or zero if it is already used by any demand.

Simulations have been preformed for *Cost266* networks by inserting 1 to 5 demands with 1 to 10 destination nodes. With these simulations I have shown that the computation time of the proposed solution is linear with the number of targets, it outperforms the results of simple heuristic methods. The results for multicast with protection can be seen in Table 1.

Table 1: Average performance of the different methods (*KDP* referees to K-Disjoint Paths, *SPLDP* to Shortest Pair of Link Disjoint Paths)

Method	Network	Cost	Time (sec)	Blocked backup paths	Used E/O Port
BEA 1^{st} generation	Cost266BT	120,3	11,3	0	29,4
BEA 30^{th} generation	Cost266BT	109,3	338,96	0	28,1
BEA 45^{th} generation	Cost266BT	108,3	508,43	0	28
BEA 100^{th} generation	Cost266BT	107,3	1132	0	27,9
KDP	Cost266BT	144,6	0,08	1,1	27,25
SPLDP	Cost266BT	144,4	1,77	0,9	27,48
BEA 1^{st} generation	Cost266LT	132,5	15,7	0	31
BEA 30^{th} generation	Cost266LT	121,4	471,3	0	29,6
BEA 45^{th} generation	Cost266LT	120,4	707	0	29,5
BEA 100^{th} generation	Cost266LT	118,83	1571,3	0	29,3
KDP	Cost266LT	180,5	0,1	0,24	32,4
SPLDP	Cost266LT	174,4	3	0,05	32,2

In Thesis 3 I have discussed the problem of physical impairment for multicast demands for cases where only optical splitting is used or where only electric splitting is used but only in the source or the targets. However, in most cases the combination of these two would provide the best possible solution. The complexity of the problem makes it impossible to solve it with algorithms guaranteeing optimality within affordable time for a network of normal size. However, it is still feasible to create quasi-optimal solutions for the given problem.

Thesis 4.2 ([J4]). *I proposed two new* BEA*-based approaches for routing unicast and multicast demands in multi-layer networks considering* PICR*. The proposed solutions are able to optimize the following cases:*

- *splitting/regeneration allowed in source and target nodes only,*
- *splitting/regeneration is allowed in any node.*

I have compared their results by extensive simulations with different heuristics and showed their ability to provide quasy-optimal solution within affordable time.

In case of *PICR* the virtual cost system has to be modified. As the demands have a new type of interference – i.e., demands have to share the power budget of a link with other demands traversing it – separated virtual cost system has to be created for every demand. For the case where electric splitting is allowed the used path search mechanisms also need a modification to incorporate the *PICR* in the search in a way that it goes up to the electric layer if the distance it takes is not affordable any more. Also the fitness has to be modified, to encapsulate the used power as well. As a consequence the main operators can be defined as follows:

- Phenotype is the result for the given problem, i.e., the routing of the demands.
- Fitness is the weighted sum of the routing cost and the used power multiplied by minus one.
- Genotype consist of the following: a virtual cost system for every demand, that will be used during routing, and routing ordered.
- The phenotype is calculated from the genotype by routing demands on a graph where edge cost is equal to the cost of the value stored for the given edge and demand in the genotype.

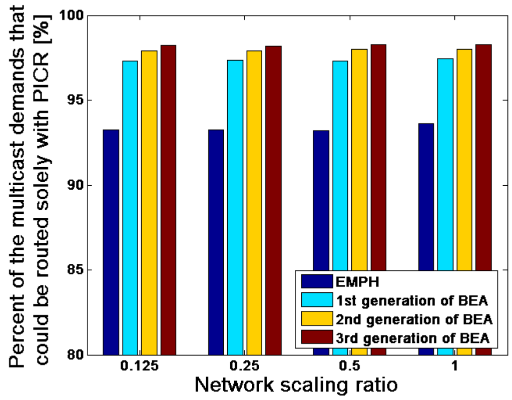
With simulations, I have confirmed the beneficial properties of the proposed methods. For details of limited regeneration case see Figure 7, for unlimited regeneration see Figure 8.

The shown *BEA* based approach can be used for other genetic algorithms or random search methods as well. Only the operators have to be modified according to the natural way of the chosen method.

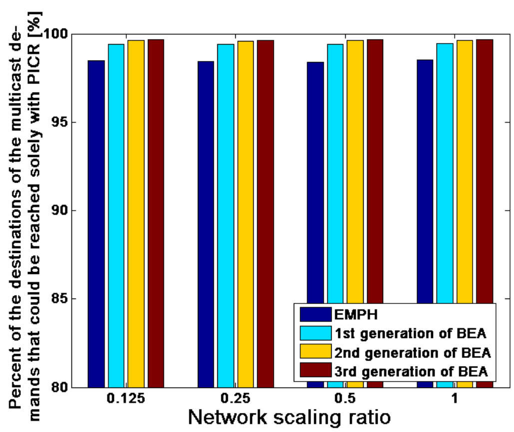
5.5 Application Possibilities

Methods shown in Section 5.1 do not have any optical network specific properties. As such, they can be applied to any problem where something have to be transported from one source to a set of destinations. Such problems can be found in Logistics or any field where control information have to be transported like army.

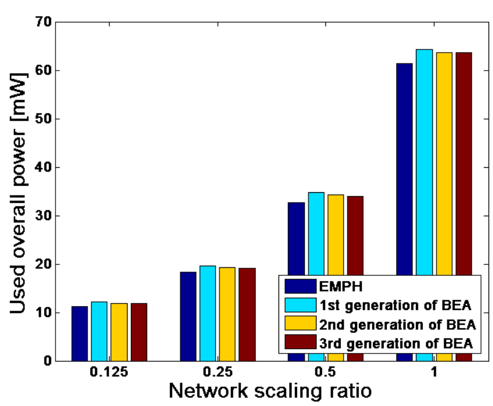
The problem of Physical Impairment Constraint Routing (*PICR*) is strongly related to the optical networks. Nevertheless, solutions proposed in the dissertation can



(a) Percent of the multicast demands that could be fully routed with PICR

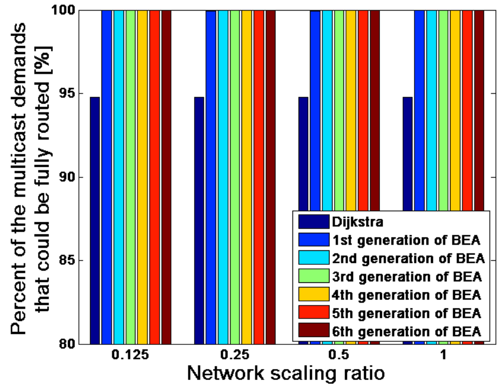


(b) Percent of destinations of multicast demands that could be reached with PICR

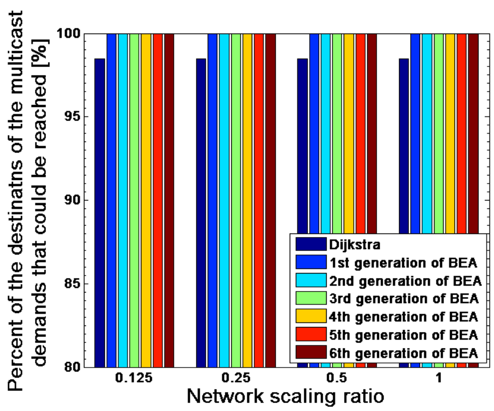


(c) Total power needed to route demands

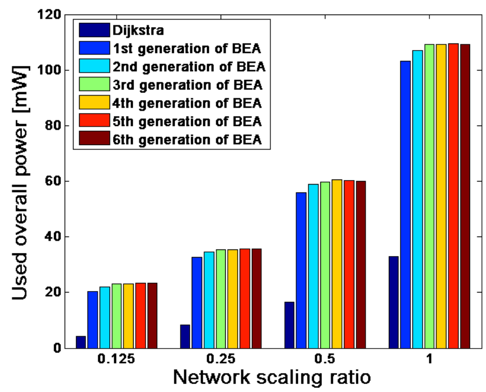
Figure 7: Results of the proposed *BEA* method for *PICR* with splitting and regeneration only at target nodes compared to *EMPH*



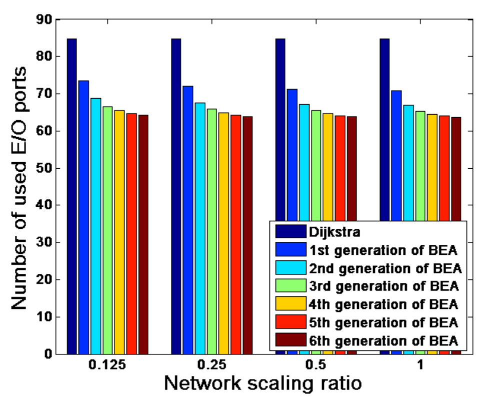
(a) Percent of the multicast demands that could be fully routed



(b) Percent of destinations of multicast demands that could be reached



(c) Total power needed to route demands



(d) Number of used E\O port functionlaity on the paths

Figure 8: Results of the proposed *BEA* method for *PICR* without limitation for the position of E/O utilization

be applies to any problem where the cost function is proportional to the distance and there are shared resources with common cost maxima. Such problems can be found in Telecommunication Networks and in Logistics.

The proposed Bacterial Evolutionary Algorithm (*BEA*) based methods for routing unicast and multicast methods are generic. They can be applied if more than one demand have to be routed and there exists a cost based heuristic for the given problem. It was successfully applied to route demands considering Shared Risk Link Groups (*SRLG*) [OC1].

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