Resource allocation for dynamic routing in WDM networks

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ABSTRACT

Dynamic routing in WDM (Wavelength Division Multiplexing) networks is achieving increasing interest due to the expected traffic growth for future optical networks. This contribution concentrates on network performance issues occurring for network operation under dynamic traffic load. In this context, routing strategies play a central role. We show that a new strategy achieves very good performance over a wide load range by making use of three beneficial components: providing multiple pre-calculated alternatives which are selected according to the network planning decisions, dynamic path search to search for routes in the cases where all pre-calculated alternatives are blocked, and an adaptive length limit to avoid on the one hand unnecessary restrictions for low traffic load, and on the other hand very long alternative routes for high traffic load. Moreover, specific effects for the influence of resource allocation strategies in photonic WDM networks are highlighted. This includes the dependence of a routing strategy on conversion degree and the influence of converter usage strategies in networks with partial conversion. The results show that an efficient routing strategy has to take into account various specific aspects of WDM networks to achieve good performance. Finally, we present how results from dynamic routing investigation can help to optimize the network planning process.

Keywords: WDM, Optical Transport Network, Routing Strategy, Dynamic Routing, Performance Evaluation, Network Planning

1 INTRODUCTION

WDM (Wavelength Division Multiplexing) technology is globally used to cope with rapidly increasing bandwidth demands in telecommunication networks, especially for wide-area transport networks. While at the moment point-to-point systems are already widely installed by many network operators, “real” optical networks including optical routing and switching are approaching. Many different architectures and application areas are described in literature most of which are based on the introduction of a WDM transport layer.[10] Two basic schemes are distinguished in literature. Either there is no conversion in the network – also called *Wavelength Routing* (WR) or *Wavelength Path* (WP) concept – or there is full conversion in the network – also called *Wavelength Interchanging* (WI) or *Virtual Wavelength Path* (VWP) concept. Recently, several concepts with *partial* or *limited* conversion were also proposed due to the high cost and still unclear benefit of wavelength converters.

The ever increasing transmission capacity of optical fibres lead to large transport streams in the core network. Since at the moment WDM networks are used for transporting a high number of low bit rate streams, and since dynamic operation of a WDM layer still suffers from technological problems, today’s WDM networks are more or less static. Therefore, many studies and investigations were performed aiming at the optimal design and dimensioning of a WDM layer for static traffic requirements. These investigations comprise static routing and wavelength assignment usually with the goal of minimising the required number of wavelengths or fibres in the network, or showing possible improvement by using wavelength converters.[3, 5]

However, in the near future a higher dynamic can be expected for the WDM layer due to several reasons. The bit rates available for end users will further increase and there will be more users connected to telecommunication networks in future. This leads not only to higher requirements for access networks, but also to more dynamic in the core network. Moreover, especially due to the increasing importance of the Internet, a higher dynamic of traffic pattern changes can be seen. With the increasing use of high bandwidth services in the Internet, these traffic changes affect higher bit rates. This stresses the importance for transport networks to be able to rapidly adapt to new traffic patterns. A possible future scenario could

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therefore be a WDM layer directly controlled by IP (Internet Protocol) routers which are able to request and release wavelength paths to distant routers. This would result in a high dynamic for long-haul WDM paths.

In addition to that, new services can be provided by a WDM layer. This comprises high bit rate protocol transparent corporate networks and “carrier’s carrier” services, maybe even with the provisioning of transparent wavelength paths. Moreover, due to the huge bit rates in such networks, advanced protection and restoration mechanisms which also require some dynamic in the network become very important. In addition to this expected increase of dynamic it has to be considered that the impact of single blocking events in the WDM layer (e. g. blocking of a wavelength path request) is drastically increasing due to the huge bit rates carried on a wavelength.

Due to these reasons the investigation of dynamic network behaviour for WDM networks is getting more important. These investigations could be combined with static planning and dimensioning tasks as described above to achieve a network solution which is optimal not only for the static requirements considered during the planning phase, but also the dynamic situation the network will face during operation.

In current literature, many work can be found dealing with dynamic routing in WDM networks. First of all, many analogies exist to dynamic routing in “classical” networks.[2, 4] But in addition, several specific aspects have to be considered for WDM networks. A recent overview describes especially the influence of wavelength conversion but investigates also the influence of topology, routing strategy, and various technological parameters, and contains various references to related work.[17] Other work considers the influence of different protection schemes on dynamic routing performance[14] or focuses on effects in ring networks.[8]

In this paper, we concentrate on Poisson traffic assumptions which is commonly used due to the uncertainty concerning behaviour of traffic in future WDM networks. Different traffic assumptions were used for other studies which could show that routing performance is influenced by traffic behaviour.[12, 13, 15, 17] Thus, all results derived for Poisson traffic have to be checked if better models based on real network measurement will become available in future. Although various traffic models are known in literature[1], it is still unclear whether they can be used for the description of traffic in a WDM transport layer.

In Section 2, we describe the large problem complexity due to many input parameters and their complex relations for the dynamic routing problem. In Section 3 our modelling approach is outlined and the simulation tool based on this modelling is introduced. Section 4 presents a number of results derived with this tool. This comprises a comparison of several routing strategies with a different number of alternatives, dynamic on-line path search (i. e. at the moment of a call request), and adaptive length limits to restrict path lengths. Following that, the strong influence of converter usage strategies for networks with partial conversion is shown. Finally, we present an example for an efficient and focused network capacity upgrade based on results from dynamic investigations. Such a “feedback loop” may help to optimize a comprehensive network planning process that also considers dynamic network operation.

Throughout the paper, a *wavelength channel* corresponds to a wavelength on a single link whereas a *wavelength path* describes a concatenation of wavelength channels, possibly with some wavelength conversion in-between. Finally, a *route* describes the geographical way of either a wavelength channel or path.

2 PROBLEM COMPLEXITY

Network blocking under dynamic traffic conditions depends on the applied routing strategy which is influenced by many parameters. Moreover, the parameters are not independent of each other which further increases problem complexity. The following list gives an overview of main parameters influencing network performance investigations.[13]

- *network topology and dimensioning*: Several topology characteristics – usually derived using a graph model of the network – such as network diameter, connectivity, number of disjoint routes between a node pair, or meshing degree have a strong influence on routing strategies. Moreover, network dimensioning concerning links (e. g. number of fibres) and nodes (e. g. size of switching network) also has a strong impact on network performance.
- *node functionality*: This relates mostly to the switching functionality of network nodes, e. g. whether there is full wavelength conversion in the node or internal blocking may occur.
- *technological constraints*: Mainly, transmission aspects are covered by this point. Examples are the maximum path length or number of transit nodes for a connection before regeneration is required, or the available number of WDM channels on a fibre.
- *traffic parameters*: This comprises offered traffic load, but also geographical distribution of traffic demands (e. g.

uniform traffic or “hot spot” traffic) and various characteristics describing traffic behaviour over time (e. g. burstiness).

- *searching strategies*: In WDM networks, there is an additional degree of freedom for a routing process due to the so-called “wavelength domain”: for the selection of a wavelength path not only the *way* but also the *wavelength* has to be determined for a request. This allows for example the following two strategies: either all possible alternatives are searched before trying another wavelength, or all possible wavelengths are checked along a given route before an alternative route is examined.[11] Moreover, for allocating a channel on a single link, various search strategies are possible (see example in Fig. 1).
- *routing strategy*: Finally, also the routing strategy itself has many parameters. Fundamental aspects are for example the selection of a (geographical) way or route for a call (e. g. according to the shortest path or according to the least loaded route), or the allowed number of alternatives and in which order they are used. In WDM networks there are also some specific aspects not known from “classical” networks. An example is the trade-off between path length and converter requirement. In the example in Fig. 2 the shorter path between *s* and *d* requires a converter due to already occupied wavelength channels, whereas the longer alternative needs no conversion but occupies more transmission capacities.

Due to the variety of parameters, the broad range of parameter values, and their complex relations several simplifications are necessary to perform quantitative studies. The following section describes assumptions made for this work and presents the chosen modelling approach.

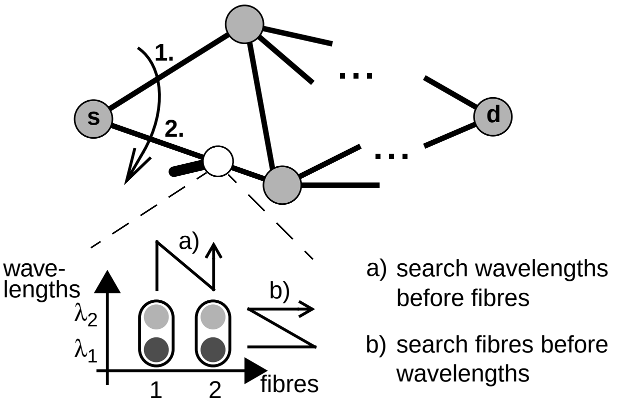

Figure 1: Search strategies for route and channel allocation in a WDM network

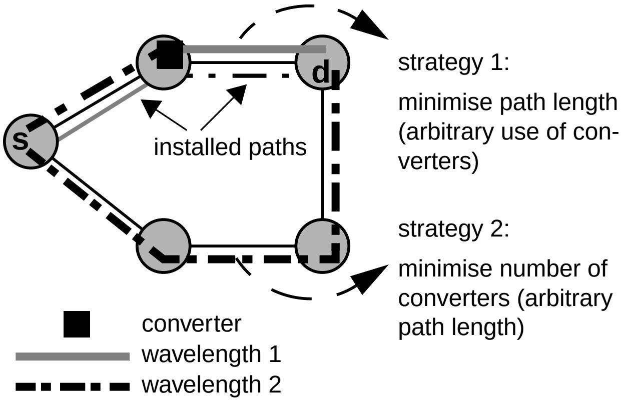

Figure 2: Different strategies for the trade-off between converter usage and path lengths

3 MODELLING APPROACH AND TOOL REALISATION

We concentrate our studies on the WDM network layer by considering routing of individual wavelength paths, i. e. a call corresponds to an end-to-end wavelength path. Concerning recommendation G.872 (former G.otn) for optical network architecture, we look to the *Optical Channel Layer Network*. Thus, neither physical transmission aspects nor higher network layers such as SDH or other client layers are considered. Moreover, the network is assumed to be in a “normal operation” state, i. e. no failure events and corresponding restoration mechanisms are considered.

The network model is shown in Fig. 3. The network nodes are connected via links which contain an arbitrary number of fibres (according to a network planning phase that has to be performed before a simulation). At a node, traffic may originate or end. To model the traffic between a source-destination node pair, we use one traffic generator for each possible node pair. This generator describes the traffic behaviour using two parameters:

- *interarrival time* between two wavelength path requests of a node pair
- *call holding* or *service time*, i. e. the time a wavelength path remains established

For the studies in this paper, we used exponential time distributions for interarrival times (corresponding to a Poisson traffic behaviour) and call holding times. Other traffic characteristics were investigated elsewhere.[12,13] To describe a call, the model covers two cases:

- *unidirectional calls*: Here, one wavelength path from source to destination is established. This scheme is applied for all studies in the following. It has to be noted, that this fully corresponds to the case of symmetrical, bidirectional traffic (which is still the usual case in today's transport networks) where paths for both directions are routed along the same way and the network dimensioning is exactly doubled compared to our case.
- *bidirectional calls*: With this scheme, which is not considered in this paper, an additional wavelength path for reverse direction is established which can be routed arbitrarily in the network.

Call handling is as follows: a call request is randomly generated by an end node. If the call cannot be established, it is lost (no special repeat behaviour is considered). If the call can be established, the corresponding wavelength channel is released after a random time span following the call holding time distribution.

Routing is managed in our model by a central routing instance (Routing Control Centre, RCC). The RCC has complete knowledge on link and node states. This model corresponds in reality to central routing (with a real RCC) or to source routing (with each node having a full picture of the whole network). This approach seems feasible since in the foreseeable future WDM networks will be widely managed by a central instance. In earlier work, we developed also a model and several strategies for decentralised routing where nodes have only a local view of the network.[11,12]

The node model is shown in Fig. 4. Basically, the nodes are assumed to have cross-connect functionality and multiple input and output links each equipped with an arbitrary number of fibres attached to a node. Additionally, wavelength paths may start or end at a node. The space switching matrix is assumed to be non-blocking. However, the conversion capability of a node may be limited. We assume a "share-per-node" structure where all converters are located in a converter pool which is shared by all wavelength paths passing through the node.[7] An empty pool corresponds to the WR (WP) case, a pool with as many converters as incoming wavelengths corresponds to the WI (VWP) case. By using a number of converters in-between, partial conversion is realised. Furthermore, we assume that all converters are able to switch from any incoming wavelength to any outgoing wavelength. In the following, we introduce the "*conversion degree*" (in %) to describe the converter pool equipment. E. g. for a conversion degree of 25% the number of converters in the pool corresponds to 25% of the number required for the WI (VWP) case. It has to be noted that due to this definition a node with many input fibres has a higher number of converters than a node with few fibres for the same conversion degree.

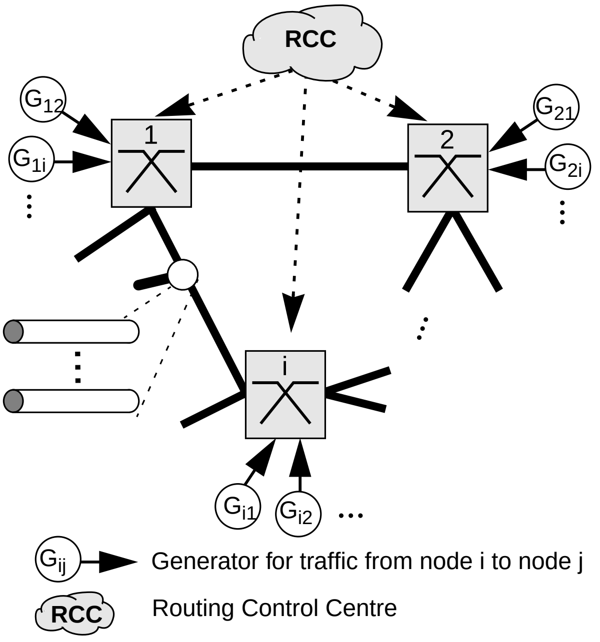

Figure 3: Network model with traffic generators and cross-connect nodes

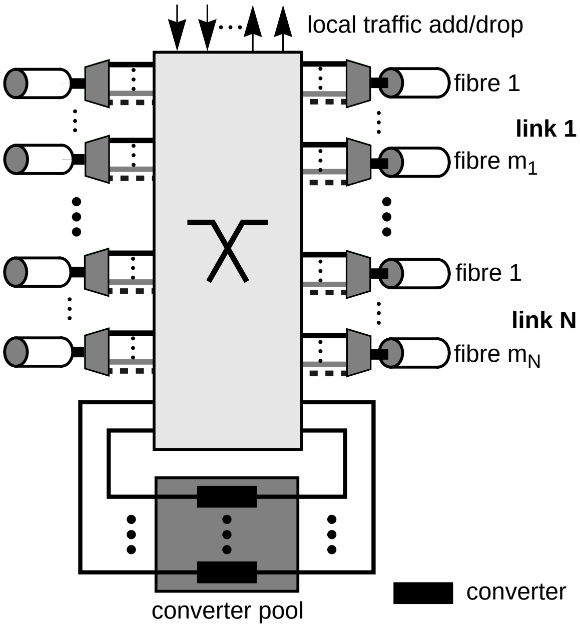

Figure 4: Model for a network node with a "Share-per-Node" converter pool

To perform quantitative studies, a discrete event simulation tool based on the model described above was implemented. The tool uses a complex object-oriented simulation library that supports simulations in many ways, e. g. by providing modules for simulation control, traffic generators, and statistical evaluations. An important design criterion for the tool was a flexible and modular structure which was achieved by an appropriate object-oriented design. In this way further enhancement of the tool, e. g. by defining new routing strategies should be simplified. Moreover, the tool allows a flexible handling of input parameters such as network topology, traffic description, or routing strategy parameters.

The tool was realised in C++ and can be executed on several platforms. It delivers a large variety of results which are usually given as mean values with confidence intervals. Examples are total network blocking, blocking of an end-to-end node pair, converter occupancy in a node, mean path lengths for successful call establishments, and lengths of alternative routes compared to the original “first way”. The following section presents several case studies performed with this tool.

4 STUDIES AND RESULTS

This section introduces general assumptions valid for all studies described in this paper. Then, several results are shown. First, we develop an adaptive dynamic routing strategy with “biased” alternatives and compare the performance with some simpler strategies. Then, the influence of additional length limit strategies is shown before a specific effect for WDM networks – the influence of converter usage strategies – is presented. Finally, we show how simulation results can help to improve network planning in a very efficient way.

4.1 Assumptions for case studies

In Section 2 it was shown that dynamic network behaviour depends on a variety of input parameters. However, to be able to achieve results it is necessary to fix several parameters in order to reduce the large problem complexity. For all studies presented in this paper we made the following assumptions. Network dimensioning was done using a planning process that is in principle based on Shortest-Path routing with an additional optimization step to avoid scarcely used links and fibres by performing re-routing of selected connections (including a new wavelength assignment if necessary). The dimensioning was done for symmetrical traffic demand derived from a simple model taking population and distance of a node pair into account. An 8 channel WDM system was assumed for all the fibres in the network. All results are presented with 95% confidence intervals.

The following two example networks are used for the case studies. These networks, which could both depict German national transport networks, differ with respect to various parameters. A comparison of some key characteristics is given in the following table while the corresponding network graphs are shown in Fig. 5 and Fig. 6.

	9-node network	**18-node network**
number of nodes	9	18
number of links (ducts)	13	29
meshing degree	2.89	3.22
network diameter*)	4	6
number of fibres	218	930
number of wavelength paths**)	944	1612

*) number of links (hops) for longest “Shortest Path” taking node distances into account

**) static number of end-to-end wavelength path requests for dimensioning = mean number of path requests for dynamic investigation

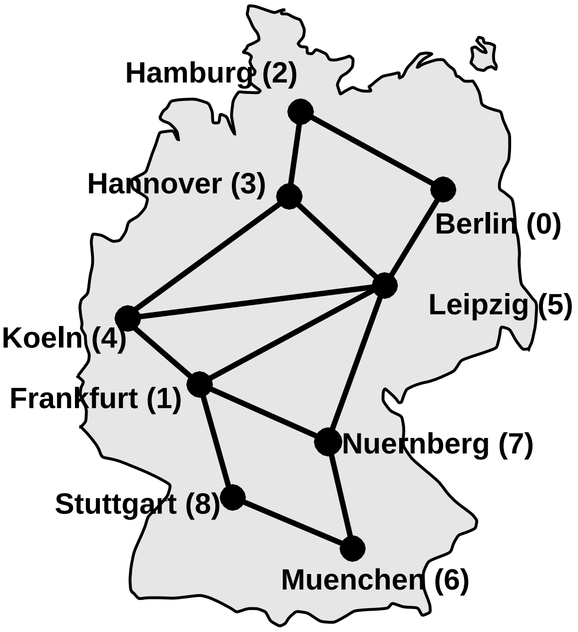

Figure 5: Example network with 9 nodes

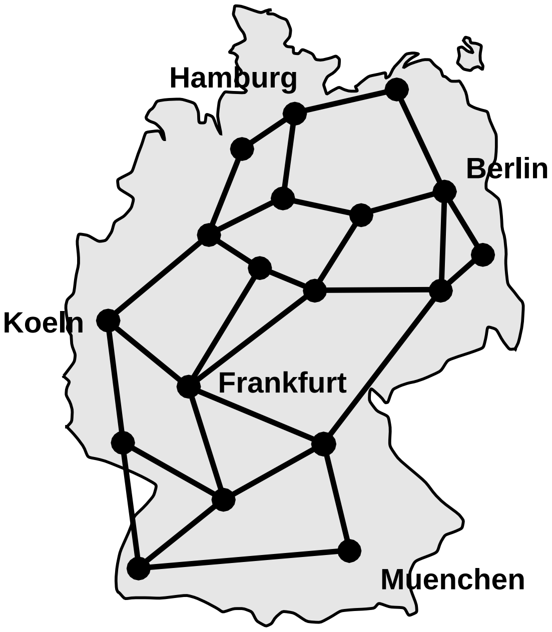

Figure 6: Example network with 18 nodes

4.2 An adaptive dynamic routing strategy with biased alternatives

This section introduces the basic routing strategy we developed and used for the following investigations. Many routing strategies for “classical” networks are broadly investigated in literature and many insights are still valid or can at least be transformed for WDM networks. However, several specific aspects have to be taken into account. In literature, it was shown that several effects also well-known from classical networks help to reduce blocking probabilities in WDM networks and thus the proposed strategies incorporate these elements, too.

First of all, a routing strategy which considers the decisions and assumptions made during network planning, especially the static routing decisions made during the planning phase, improves performance. Such schemes were also called “biased” routing schemes.[16] In our case, we mainly applied Shortest-Path routing to determine the necessary network dimensioning, and therefore dynamic routing is biased accordingly. However, such a scheme implies that the traffic patterns considered during planning and those considered during dynamic investigations are similar.

Routing performance strongly depends on the number of alternatives allowed for routing a call request. Multiple alternatives reduce blocking significantly compared to the case where only a single route is allowed. These so-called “alternative routing” schemes can be further improved by an additional route calculation at the moment of a connection request.[2, 6, 9]

To show the influence of these elements we compare the following basic routing strategies:[13]

- *Fixed Source Routing* (FSR): This simple strategy allows only one fixed route for each possible connection request. If no wavelength path (which may include wavelength conversion if possible) along this route can be found, the request is blocked.
- *Alternative Source Routing on Link-Disjoint paths* (ASR-LD): This strategy provides for each shortest route between a node pair a set of alternatives which are disjoint at least to one of the links of the original route, respectively.
- *Alternative Source Routing on Completely Disjoint paths* (ASR-CD): This strategy requires completely link disjoint alternatives. In general, performance results are comparable to ASR-LD, but slightly worse due to the higher restrictions for the routing process. Therefore, this strategy is not shown in the following figures.
- *Adaptive Dynamic Routing with x pre-calculated paths* (ADRx): This strategy is the most complex strategy shown here and allows a dynamic calculation of a new path in case all pre-calculated paths are blocked. For this dynamic calculation, links loaded above a (configurable) threshold are excluded.

Fig. 7 shows some results for the following parameter settings. The 18-node network is investigated for 0% and 25% conversion degree in the network nodes. The ADRx strategy is shown for 2 pre-calculated alternatives (ADR2). The *x* axes in Fig. 7 presents the offered load (i. e. the mean value of the assumed Poisson traffic) in relation to the so-called “static traffic demand”, which describes the static traffic demand assumed for network dimensioning. The main results from the figure – which are representative for many studies we performed – are the following:

- **influence of number of alternatives and dynamic route calculation**: The results show that in principle all strategies, which allow multiple alternatives, perform much better than FSR. If the lines for a given conversion degree are compared (thin lines for 0% conversion, thick lines for 100% conversion), we see that ADR2 achieves lowest blocking values over a broad load range. In the given scenario, ADR2 performs even slightly better than ASR-LD with 25% conversion showing the great importance and influence of a dynamic path calculation with a central view on the network state.
- **influence of offered load**: It can be seen that the statements above are only valid for the “low load” area (up to approximately 85% in our case study), whereas for higher loads the different strategies converge. We could show that for even higher loads an intersection of the curves for different strategies occurs and that FSR achieves best performance.[13] This effect can be explained by looking to the path lengths (given in number of links) shown for the different strategies in Fig. 8. The mean number of links per connection is reduced for the FSR strategy with increasing load because connection requests for nodes with a large distance are more probably to be blocked. For the other strategies, the mean length is increasing because some paths are accommodated along longer alternatives, but the price is that multiple short connections then might be blocked leading to higher overall blocking.
- **influence of conversion degree**: For the FSR scheme only one line is shown since the results for all conversion degrees (from 0 to 100%) were very close together. The lines for 100 % conversion degree are not show in the figure, but they are nearly identical to the lines achieved for 25% conversion. Thus one conclusion is that a small number of converters may improve network throughput under dynamic conditions but a 100% conversion provides almost no benefit compared to a smaller conversion degree. This result was confirmed in many other investigations for static as well as for dynamic conditions (see for example in [3, 5]).

Finally, when considering absolute values for total network blocking we can state the following. To achieve an acceptable network blocking the mean load for dynamic traffic behaviour has to be significantly lower than the static load used for network dimensioning. In the example shown here, the load should be kept below 80% for reasonable blocking values (although it has to be noted that the specific numbers are strongly dependent on the considered network case study). However, a routing strategy also has to perform well for “overload” scenarios and therefore the following section describes an important strategy extension.

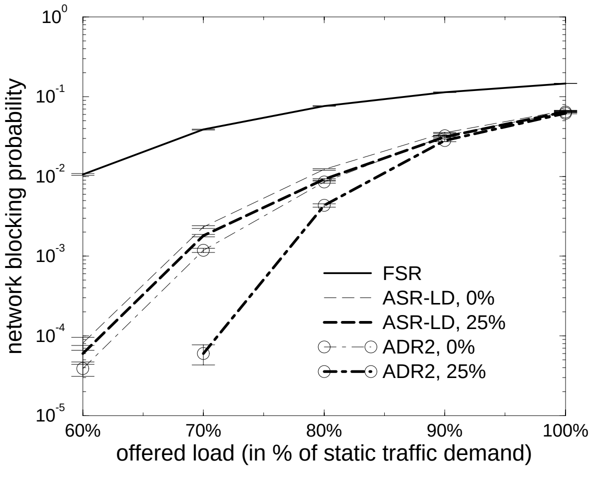

Figure 7: Comparison of different basic routing strategies for the 18-node network and two conversion degrees (0%; 25%)

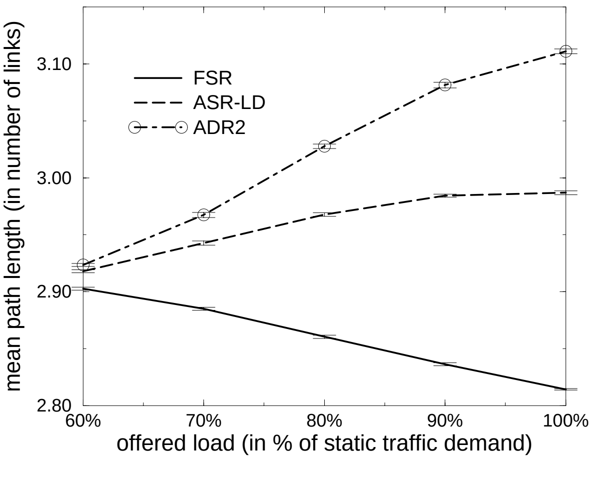

Figure 8: Mean path length (in number of links) for the 18-node network and 25% conversion degree

4.3 Length limit strategies

The above mentioned behaviour for high load leads to the conclusion that some kind of additional “limitation strategy” could be beneficial for the overall performance. In this section we introduce and compare several limitation strategies for the following representative scenario: the 9-node network with 25% conversion degree is investigated for the ADR2 strategy.

The simplest limitation strategy is to set an absolute limit for any path length. In Fig. 9 the influence of such a strategy is shown for several limit values. We have chosen the number of hops as length parameter. It can be seen that a limit of 3 hops is too small since several node pairs are not able at all to establish a wavelength path. On the other hand, this limit leads to lowest blocking for very high load. Although the other limitation strategies are rather close together, we can state that a limit of 4 hops achieves good performance for very high loads, but results in higher blocking for low network load compared to a limit of 5 hops or the case without limit.

Thus, although an “absolute limit strategy” is simple to realise it has the following main drawbacks:

- there are unnecessary restrictions for low network load (which will often be the main operational area)
- unfairness occurs because node pairs with a short distance may still have many alternatives while in the worst case other node pairs may not be able at all to establish a connection. This aspect is getting more critical with increasing network size due to the increasing length differences of node pairs.

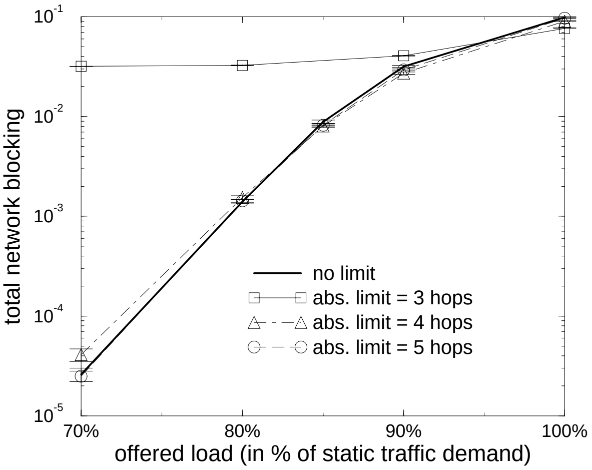

Figure 9: Comparison of different absolute length limits for the ADR2 strategy (9-node network, 25% conversion)

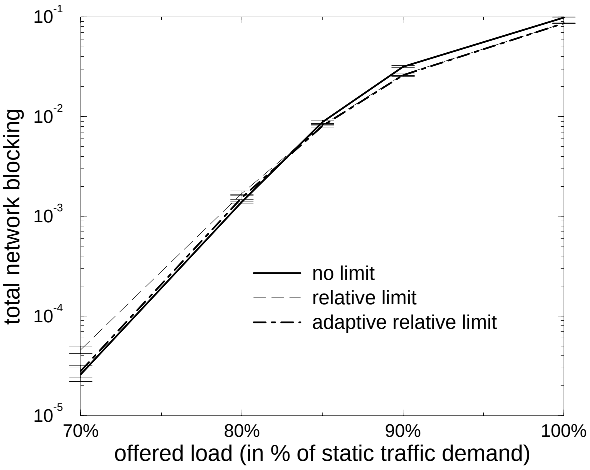

Figure 10: Relative and adaptive length limits for the ADR2 strategy (9-node network, 25% conversion)

Therefore we propose the following improved strategies:

- **relative length limit**: With this strategy, length limits consider the length of the shortest route (i. e. the first alternative). Again, such a relative limit can be realised in various ways. After a detailed consideration of the network topology and traffic pattern, we have chosen an approach for the 9-node network where the length of alternative routes is limited to k_i times the original length of a route according to the following table:

number of hops for “Shortest Path”	k_i	maximum number of hops for alternative route
1	3	3
2	1.5	3
3	1.33	4
4	1.25	5

- **adaptive length limit**: In addition to the relative limits described above, this strategy also considers the load on network links. Only links with a load higher than a threshold are included in the limitation process. Such an adaptive consideration can be combined with various other strategies. However, a difficulty occurs for WR networks. In this case the number of channels occupied on a link is no longer a sufficient measure due to the wavelength continuity constraint: a connection request arriving at a link on a certain wavelength may be blocked although some other wavelengths are still free. Therefore, threshold mechanisms are especially useful with sufficient conversion.

Some results for the scenario described above can be found in Fig. 10. The relative length limit achieves a good performance for high loads but still shows unnecessary blocking increase for low loads. This is significantly improved by using the adaptive strategy (with a limit equalling 90% load on a link for the results in the figure). In conclusion, the results show that a biased, alternative, dynamic and adaptive strategy achieves very good performance results over the whole load range.

4.4 Converter usage strategies

WDM cross-connect networks offer several new degrees of freedom for routing decisions. In literature, the influence and interworking of different “wavelength selection” and “path selection” algorithms was already investigated for WP networks.[9] However, there are some more degrees of freedom which were not investigated so far. In the following, we present the influence of the converter usage strategy. This effect is specific for WDM networks and plays an important role in networks with limited wavelength conversion. We investigate two different strategies:

- *MinOff* tries to minimize the path lengths while using converters arbitrarily (this strategy was used for all studies described above)
- *MinOn* tries to minimize the number of converters while accepting longer routes

For the results in Fig. 11 and Fig. 12 we investigated the ADR strategy with 1 or 2 pre-calculated alternatives and no length limit for the 9- node network. Again, we have to distinguish different load levels. Fig. 11 shows the network blocking probability versus number of converters per fibre (0 equals “no conversion”, 8 equals “full conversion”) for a network load of 80% of the static traffic demand. We see that already few converters decrease blocking significantly whereas for more than 2 converters per fibre (equalling 25% conversion) no further improvement can be seen (similar effects are well-known for many static network dimensioning problems). But we see also the strong influence of the *MinOn* strategy for low conversion degree: starting from identical blocking values for “no conversion”, blocking is quickly and significantly reduced with an increasing number of converters and the optimum performance is already achieved with a conversion degree of only ~6% (equalling 0.5 converters per fibre). For higher conversion degrees *MinOn* and *MinOff* strategies converge. Moreover, the results show that for low conversion degree ADR2 performs slightly better than ADR1, which is expected due to the additional pre-calculated biased route. For a higher conversion degree the results are comparable.

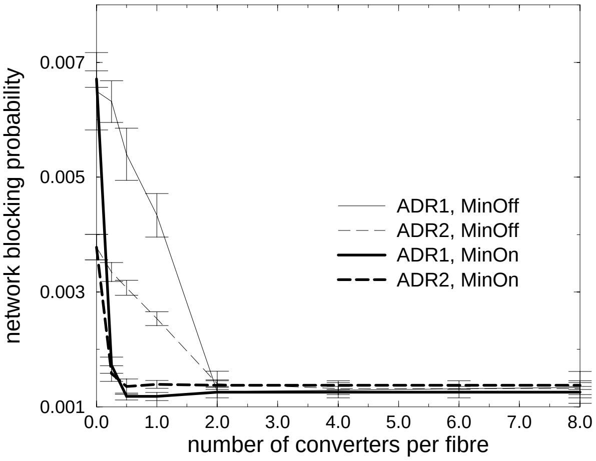

Figure 11: Network blocking for different converter usage strategies and conversion degrees (80% network load)

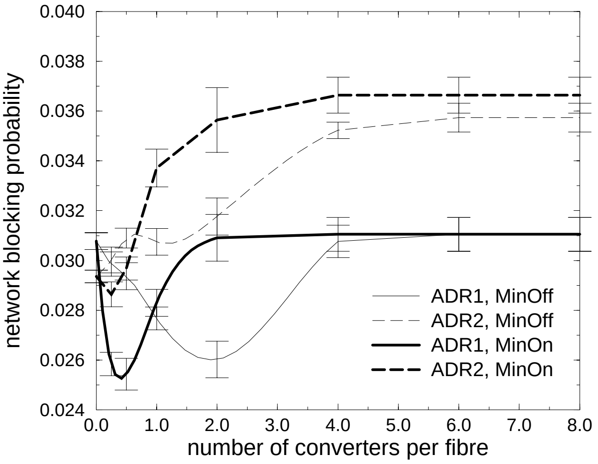

Figure 12: Network blocking for different converter usage strategies and conversion degrees (90% network load)

The situation changes for 90% network load (Fig. 12). In this case, we see several effects very astonishing at the first glance. First, ADR2 leads now to higher blocking values than ADR1 for a broad range of conversion degree. Second, only for a very low conversion degree additional converters reduce network blocking. For more converters, blocking is increasing, for ADR2 even above the value for 0 converters. The reason is that in a congested (heavy loaded) network more converters allow some longer paths which on the other hand may block several shorter paths. Although in general the difference between ADR1 and ADR2 is larger than the difference between *MinOn* and *MinOff*, for low conversion degree the converter usage strategy still influences blocking significantly.

From the results shown we can conclude that an optimal routing strategy for WDM networks has to be adapted to the available conversion capability of the network as well as the network load due to different behaviour for low and high network load.

Another interesting result is shown in Fig. 13 and Fig. 14 which present the converter occupancy in several nodes versus number of converters per fibre for both strategies, *MinOn* and *MinOff*. For this study ADR2 was applied for the 9-node network with a load of 80%.

Fig. 13 shows the converter occupancy for the *MinOn* strategy. First, the expected result can be confirmed that the occupancy in border nodes is significantly lower than in central network nodes. Moreover, we see that already for rather low conversion degree the converter usage reaches very low values. This changes significantly for the *MinOff* strategy which leads to generally higher converter occupancy levels (Fig. 14). Moreover, we can see that the relative order of nodes according to the occupancy level may change: e. g. Koeln has the lowest occupancy for *MinOn* but requires a rather high number of converters for *MinOff*.

Results like this allow an optimized network dimensioning by implementing wavelength converters at the optimum locations. But again such a focused network upgrade not only depends on given input parameters as topology or traffic but also on the routing strategy.

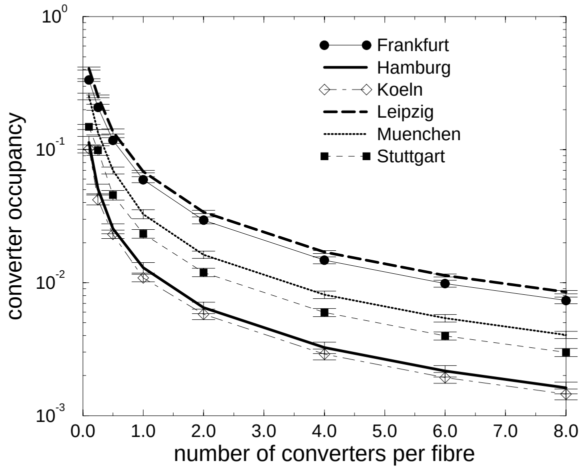

Figure 13: Converter occupancy for ADR2 applied to the 9-node network with 80% load (*MinOn*)

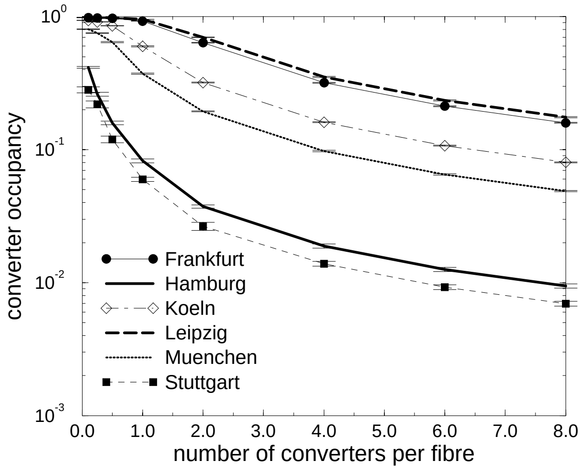

Figure 14: Converter occupancy for ADR2 applied to the 9-node network with 80% load (*MinOff*)

4.5 Network dimensioning improvement using simulation results

Finally, we want to show how simulative network investigations for dynamic load can help to optimize link dimensioning. In the following, we show the end-to-end blocking probability for different node pairs. The node numbers used in Fig. 15 and Fig. 16 can be found in the network graph in Fig. 5. Each line describes the blocking of calls originating at the node assigned to this line and ending at the node depicted on the *x* axes. For the studies, the ADR2 strategy with minimisation of converter usage (*MinOn*) was applied to the 9-node network with a conversion degree of 12.5% (1 converter per fibre) and a network load of 80% of the static traffic demand.

Fig. 15 gives the results for the “standard” network dimensioning (used for studies presented so far) for selected node pairs. The picture allows several conclusions:

- We see for some nodes a tendency for higher blocking values compared to other nodes. In the example, nodes 2, 6, and especially node 8 show this behaviour.
- Moreover, we see that all connections starting in Stuttgart (node 8, solid line) suffer from a significantly higher blocking than the other connections (the lines for other nodes not shown in the graph are in the region of the dashed lines).

This insight has been used for a selected network upgrade: the link between Stuttgart and Frankfurt has been equipped with one additional fibre for each direction. The result is shown in Fig. 16. Now, all connections are in the same region concerning blocking values. Moreover, the total network blocking was also decreased significantly: from 0.001389 +/- 0.000069 for the standard dimensioning to 0.000744 +/- 0.000095 for the case with increased dimensioning. This shows that already a very small (the two additional fibres correspond to a total network capacity increase of only 0.92%) but well placed capacity increase can lead to a drastically network performance increase (~46% for the mean values). In addition, fairness concerning different node pairs is increased as well. Finally, it is remarkable that the right place for a capacity increase could not be found by looking to the blocking events occurring on a link. These statistics show no unusual behaviour of the link Stuttgart-Frankfurt.

As a conclusion we can state that careful evaluation of the results achieved by dynamic investigations can constitute a valuable feedback for an overall network planning process that takes network operation into account. It allows to avoid unnecessary network equipment (shown for the number of converters in this paper), and to achieve significant performance improvement already with small but well placed additional network capacities (shown for additional link capacity in this paper).

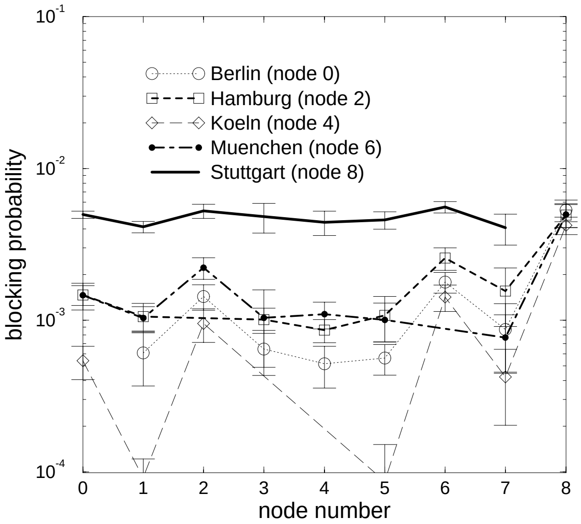

Figure 15: End-to-end blocking without capacity increase (for ADR2 strategy with *MinOn* applied to 9-node network loaded with 80% and 12.5% conversion degree)

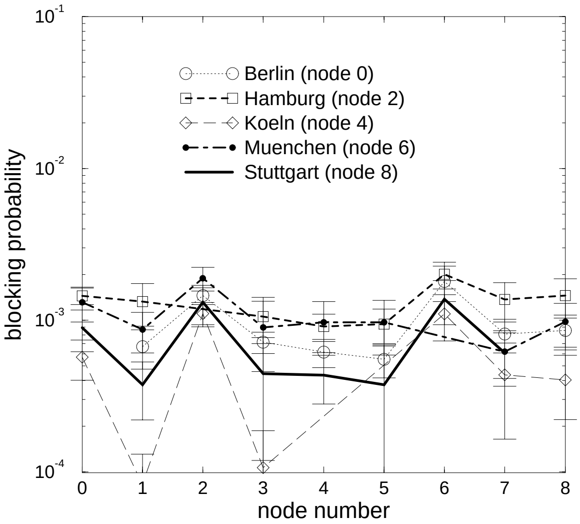

Figure 16: End-to-end blocking with small capacity increase on one link (for ADR2 strategy with *MinOn* applied to 9-node network loaded with 80% and 12.5% conversion degree)

5 CONCLUSIONS AND OUTLOOK

In this paper we investigated several routing strategies and specific effects for dynamic wavelength path routing in a WDM transport network based on cross-connects. Several cases for conversion capability in the nodes were considered, including partial conversion. A new routing strategy was developed based on pre-calculation of “biased” alternatives (i.e. oriented according to the network design rules), a dynamic path search in case all alternatives are blocked, and an adaptive consideration of length limits to achieve good performance over the whole load range. We presented the influence of various parameters such as number of available alternative routes, offered load, and conversion degree on network performance.

Furthermore, two strategies for converter usage were presented and compared. We pointed out the importance of converter usage strategies for networks with partial conversion. The conclusion is that the routing process has to consider subtle effects, which are partly new compared to classical networks, especially for low conversion degree and for high network load in WDM networks. Finally, we could show that results from a dynamic network investigation provide a valuable feedback for a comprehensive network planning process by allowing an efficient and well located installation of transmission and switching equipment in the network.

Further work could improve this insight by providing some kind of “automatic feedback loop” for the network planning process to take results from the investigation of dynamic behaviour for dimensioning of nodes and links into account automatically. Moreover, a better traffic description for various network scenarios (including transport of classical SDH networks as well as IP networks by the WDM layer) should be developed and considered for the routing process. Finally, other routing strategies and search strategies for resource allocation could be developed and compared to the strategies described in this paper.

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