Design Parameters for Dynamic Routing in WDM Cross-Connect Networks

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Abstract

This paper investigates the network performance for dynamic traffic conditions, i. e. randomly arriving wavelength channel requests and releases. To handle dynamic traffic, a routing process is required to decide which path is selected for each arriving request. This paper discusses several parameters which influence the routing performance. Examples are the network topology and resource allocation mechanisms for the routing process. Several routing strategies are developed and compared. A new strategy considering multiple "biased" alternatives, dynamic path search, and an adaptive length limit which achieves good performance over a wide load range is presented. Finally, the influence of some traffic parameters on the routing performance is investigated in detail.

Keywords

WDM, Optical Transport Network, Dynamic Routing, Performance Evaluation

1 Introduction

The great progress of WDM technology leads to an increasing number of point-to-point links in operation today and real WDM networks will appear soon, first for wide area networks due to the huge bandwidth required for future telecommunications infrastructure. After several years of research focusing on network design and planning (mostly based on static traffic assumptions), very recently dynamic investigations gain increasing interest. Especially the performance of routing strategies under dynamic traffic conditions (i. e. randomly arriving and finishing call requests) is an important topic. Although today traffic in WDM transport networks is more or less static, dynamic will increase in future due to higher bit rates, new services in the network (e.g. leased wavelength service), and (re-) routing and restoration tasks. Moreover, the importance of single blocking events (e. g. blocking of a wavelength channel) is drastically increasing due to the huge bit rates carried on a wavelength. Thus, even small effects occurring for dynamic conditions may have a big impact.

The goal of this paper is to investigate the network performance under dynamic traffic conditions. Here, performance considers traffic aspects. It can be described by the network throughput, i. e. the number of wavelength channels between a source-destination pair in a WDM network. An equivalent measure is network blocking, i. e. the probability that a wavelength channel request has to be rejected. It is the goal of routing strategies to minimise the total network blocking.

In the near future, WDM networks will comprise relatively few nodes and circuit-switching on a wavelength channel basis will be used. Moreover, call holding times (i. e. holding times for wavelength channels, the expression “service time” is also used in the following) are expected to be longer than in today’s networks. Therefore, the paper concentrates on routing strategies that can be performed by a *central* instance, whereas in [7, 8, 9] the focus was on *distributed* or *decentral* strategies.

All studies were carried out for a possible German backbone network with bi-directional links (Figure 1). Although rather small, all effects shown in this paper can be demonstrated using this network. The number of fibres per link and the nodes were dimensioned according to an optimisation process with a tendency to use shortest path connections while avoiding scarcely occupied fibres. The dimensioning was done for the so-called *static traffic demand* which takes population densities and node distances into account. We assumed 8 wavelength channels per fibre and allowed an arbitrary number of fibres for the links.

The nodes were assumed to be cross-connects which allow switching of wavelength channels from any input to any output. For wavelength conversion capability, we considered several options. In addition to “no conversion” - also called *Wavelength Routing* concept (WR) or *Wavelength Path* concept (WP) - and “full conversion” - also called *Wavelength Interchanging* concept (WI) or *Virtual Wavelength Path* concept (VWP) - also partial conversion is possible. There are many variants to realise partial conversion. We concentrate in this paper on a “share-per-node” architecture in which all wavelength channels passing a node share a common pool of converters. Furthermore, we also do not consider specific protection or restoration scenarios.

The studies were carried out by means of discrete-event simulations. The

simulations were performed by using an object-oriented software tool written in C++. All results in this paper are given with 95% confidence intervals.

The paper is structured as follows. First it discusses various parameters influencing the routing performance (Section 2). In Section 3 we investigate several routing strategies and show that a new strategy based on three components (multiple "biased" alternatives, dynamic path search, and an adaptive length limit) achieves very good performance over a wide load range. Finally, in Section 4 the influence of some traffic parameters is highlighted.

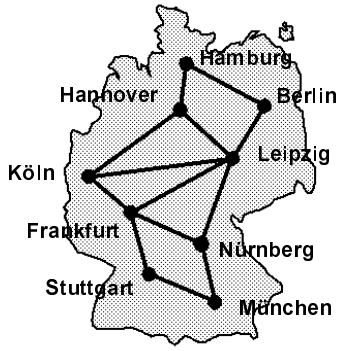

Figure 1: Example network topology for which the studies were performed

2 Parameters for the dynamic routing problem

There are many different parameters which influence network blocking. The problem complexity is increased further due to the fact that many parameters are interdependent: the impact of one parameter on the blocking may depend on the value of another parameter. This leads to the conclusion that one has to be careful with results obtained by variations of only one parameter. This section gives various examples for parameters and describes the assumptions made for the studies in the following sections.

Network topology and dimensioning

A network topology can be modelled by a graph, which in general is directed and weighted. This graph plays a very important role for routing investigations since it determines many parameters which directly influence a routing method. One example is the *diameter* of a network which is usually defined as the longest "Shortest Path" for all node pairs, i. e. the largest distance occurring in the graph. Although arbitrary measures could be used for describing a path length (e. g. geographical distance, cost, etc.), a very useful measure is the "number of hops".

Another important parameter defined by the graph is the number of disjoint alternative paths available for a specific original path. In more detail, node disjoint and link disjoint paths can be considered. For both cases, one can further distinguish between fully or only partially disjoint paths. Moreover, also the relation of the original and alternative path lengths is an important indication for the additional resources required by alternatives. A routing strategy should consider the distribution of path lengths for original as well as for alternative paths, i. e. the number of one hop paths, two hop paths, etc.

For the example network described in Section 1, a detailed investigation (focusing on link disjoint paths) leads amongst others to the following conclusions which were taken into account for the development of an appropriate parameter setting for the strategies described in Section 3.

- For all node pairs, there are at least two completely disjoint paths.
- There are relatively few node pairs which can be connected with more than two completely disjoint paths.
- The “pair of shortest disjoint paths” often differs from the combination of the “shortest path” and the completely disjoint “second shortest path”.
- When comparing partially and fully disjoint paths between a node pair, in general there are more partially disjoint paths and these paths are shorter for a given original path length.

The dimensioning of the network is another important parameter closely related to the topology. It comprises dimensioning of links (e. g. number of fibres) as well as nodes (e. g. number of available switching elements) and has a strong influence on network performance parameters. The dimensioning strongly depends on the traffic parameters (see below).

Node functionality

The node functionality - and related to this the network architecture - determines the possibilities available for a routing process. The two basic node types of specific interest for WDM networks are cross-connects (CC) and add/drop multiplexers (ADM). For both node types there are many variants with different functionality concerning switching (e. g. internal blocking), wavelength conversion (no conversion, full conversion, or partial conversion) or additional features such as regeneration. There are also many realisation approaches leading to the same functionality, but for network performance investigations implementation details are of less importance.

Some more aspects occur when considering the protection and restoration methods. The capabilities of a network depend on the node functionality and restrictions for the routing process may result (e. g. it could be required that for each working path a completely disjoint protection path has to be found). The node model could be refined further by taking into account additional technological or physical limitations.

Transmission functionality

There are also many technological parameters describing the transmission functionality which influence routing performance. An example is the available bandwidth for a link. For WDM networks, the total capacity results from the bit rate per wavelength channel multiplied by the available number of wavelength channels per fibre. In many scenarios (especially when there is not full conversion in the network), not only the total capacity is important, but also in which way this capacity is achieved, i. e. the actual values for the bit rate and the number of channels.

Another technological parameter is the transmission distance achievable for a certain bit rate. Related to this are the regenerator requirements to achieve a certain transmission performance. These parameters have a strong influence on the network cost, but they may also influence the routing functionality (for example, some long routes may not be realisable although the resources are available).

Strategies for the routing process

Obviously, the routing strategy plays a central role for network performance under dynamic traffic conditions. Many different "basic" routing strategies can be distinguished, such as *shortest-path routing*, *fixed source routing*, or *least-loaded link routing*. In addition, various "search strategies" for network resources exist which also can influence network performance.

For routing in WDM networks, many well-known strategies from "classical" networks can be adapted, but several specific features of WDM networks have to be taken into account. Some examples are given in the following whereas in Section 3 several new strategies are developed and investigated in detail.

WDM networks with multiple fibres on a link provide an additional degree of freedom for the channel assignment (due to the so-called *wavelength domain*). It is possible either to search along all fibres for one wavelength before changing to the next wavelength, or to search along all wavelengths on one fibre before going to the next fibre (see Figure 2a). In WDM networks with partial or no conversion, these two strategies usually lead to different network performance.

The mentioned wavelength domain leads also to an additional degree of freedom for the routing decisions. To route a path between a node pair, in addition to the *way* also a *wavelength* has to be chosen. This allows for example two strategies called "path priority" and "wavelength priority". The "wavelength priority" strategy performs a search among all possible routes for a given wavelength before trying another wavelength (i. e. colour), whereas the "path priority" strategy checks all wavelengths on a given route before trying another route (see Figure 2b). These strategies result in different network performance and were investigated in [8]. Again, this effect is only important for networks with restricted or no conversion capability.

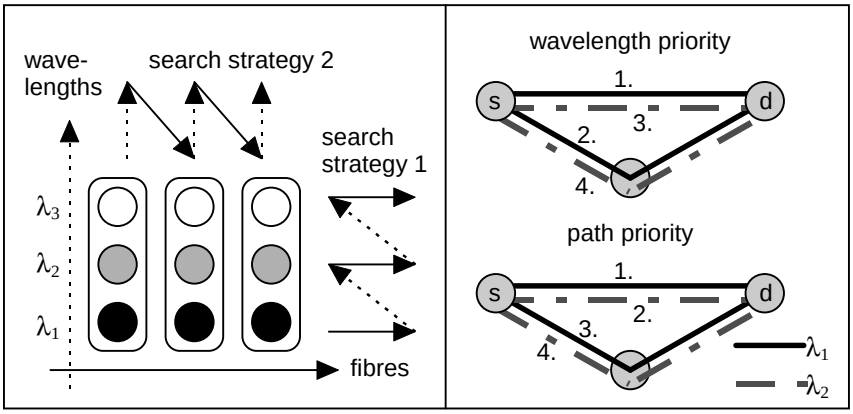

Figure 2: a) search strategies for channel allocation on a WDM link
b) priorities for routing decisions

Another example are converter usage strategies which are important for networks with partial conversion. In this case, there is often a trade-off between the length of a path and the required number of converters. For the example shown in Figure 3 there are two options for establishing a path between the nodes *s* and *d*: there is a short route (2 hops) which requires a converter due to already occupied wavelength channels along this route, and there is a longer route (3 hops) which doesn't require any conversion. It was shown in [9] that different converter usage strategies have a strong impact on the achievable network performance and that there are situations in which more converters lead to a blocking increase due to disadvantageous routing decisions.

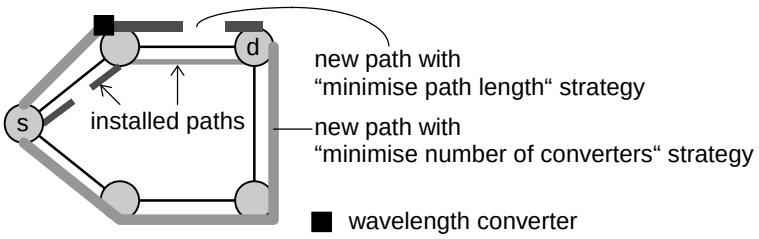

Figure 3: Converter usage strategies

Traffic parameters

The traffic assumptions made for a routing investigation have a strong influence on performance results. It is always difficult to find traffic descriptions which are on one hand accurate enough to cover all effects, but are on the other hand as simple as possible to simplify the analytical calculations or the required software tools for an investigation. The following parameters can be distinguished for a

traffic description:

- *traffic volume*: This parameter describes the absolute traffic values. For WDM networks, usually the number of wavelength channels between a node pair is considered.
- *traffic distribution*: This parameter describes the distribution of traffic among the network nodes. Common examples are a uniform distribution (e. g. the same traffic between all node pairs) or a distance dependent traffic pattern (e. g. decreasing traffic with increasing node distance).
- *traffic characteristics*: This parameter describes the behaviour of traffic streams. It is well-known from many traffic theoretical work that traffic behaviour strongly influences network performance. In literature, many traffic models are reported [1]. For circuit-switched networks, a consideration of the call interarrival time and the call holding time behaviour is often applied. We also use this approach by describing these two parameters with their mean value and their coefficient of variation (see Section 4).

For WDM networks, the traffic description problem is further complicated because there are not enough measurements available up to now. Thus, the traffic modelling is mostly based on estimations and it has to be checked carefully in which way the results of investigations depend on the traffic parameters. In Section 4, we investigate this point in more detail and show the influence of call interarrival and call holding time parameters on the routing performance.

3 A new adaptive dynamic routing strategy with biased alternatives

It was shown in literature that several effects help to reduce network blocking. First, the provision of several alternatives reduces blocking significantly compared to a single routing possibility. This is a fact well-known from all “classical” routing problems. Second, it is an advantage to consider the decisions made during network planning for the routing process. Such a “biased” routing prefers routing along the paths determined during network planning which leads to a better performance [6]. Third, it was shown that a dynamic route calculation at the moment of a connection request further improves routing performance [2, 4, 5]. In the following, we develop and compare several strategies which take these aspects into account. Then, we improve the resulting favourite strategy with a new feature which restricts the path length for high load situations in the network.

3.1 Comparison of different routing strategies

In this subsection, we compare several central strategies and one example of a decentral routing method. To realise a central strategy, all network information is collected in a central *routing control centre* (RCC). The RCC therefore has a complete overview of the network state and is responsible for all routing decisions, which are reported to the switching nodes. In contrast, a decentral

strategy does not require any central instance but can be realised by interactions of the network switching nodes. However, it has to be mentioned that a decentral strategy could also be realised by an RCC.

Strategies

The following basically different central strategies are compared, although it has to be mentioned that for all strategies several variations concerning algorithmic details are possible:

- *Fixed Source Routing* (FSR) is the most simple strategy since it allows only one fixed path for a connection request. However, in our case this path is chosen according to the path selected during network planning for a certain connection request (in most cases, this was the shortest path).
- *Alternative Source Routing on x Complete-Disjoint paths* (ASR-xCD) provides for each shortest path between a node pair a set of *x* alternatives which are completely disjoint to the original path.
- *Alternative Source Routing on Link-Disjoint paths* (ASR-LD) provides for each shortest path between a node pair a set of alternatives which are disjoint to *one* of the links of the original path, respectively. Thus, in contrast to the ASR-xCD strategy, parts of the original shortest paths can be reused. Moreover, a completely disjoint path is also included into the list of alternatives.
- *Adaptive Dynamic Routing* (ADRx) is the most complex strategy. Similar to the strategies described above, it first provides *x* pre-calculated biased paths, but additionally a dynamic calculation of a new path is possible in case all pre-calculated paths are blocked. This dynamic calculation performs a shortest path search excluding all blocked links from the network topology.

For comparison, we added a decentral routing strategy which performs a hop-by-hop routing and does not require any network state information but can work purely local: *Sequential-Office Control with crankback* (SOCc) allows each node to select between various (local) routing options, and if no continuation is possible, routing control is given back to the predecessor node [3]. A more detailed investigation of this and other hop-by-hop strategies for WDM networks is contained in [7, 8, 9].

Results

The following results were achieved for Poisson traffic assumptions. This means that the interarrival time between two wavelength channel requests for a certain node pair as well as the holding time of a wavelength channel are negative-exponentially distributed. The offered load is measured in relation to the static traffic demand which was assumed for network dimensioning: a value of 80% describes a scenario in which the mean value of the traffic demand between any node pair is reduced to 80% of the static traffic requirement used during network planning.

For the results presented in Figure 4, a partial conversion (25%) in the network is assumed although the effects described in the following are similar for an arbitrary conversion degree. For the share-per-node cross-connects the number of converters in the pool depends on the number of fibres attached to that node. 25% conversion degree means that each node has a number of converters in the pool equalling 25% of the number of wavelength channels passing that cross-connect.

Thus, the absolute number of converters increases with the node size.

Figure 4 shows that we have to distinguish between a “low load area” and a “high load area”. For low load (up to approximately 80% load), all strategies with multiple alternatives are much better than FSR. For the ASR strategies, only ASR-LD is shown, because it turned out that this strategy is slightly better than using completely disjoint paths (ASR-xCD) due to the fact that parts of the original shortest paths can be reused. SOCc achieves rather good performance, but is slightly outperformed by ADR2 which benefits from the central view on the whole network state and achieves lowest blocking values.

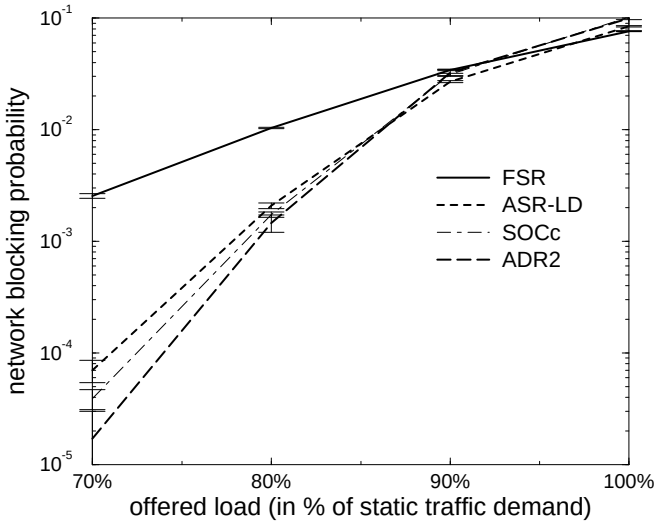

Figure 4: Comparison of routing strategies with a different number of alternatives

However, the picture changes for high load. Although usually a network should be operated in an area with less blocking, a routing process has to be capable to cope also such unavoidable overload situations. For high load, the more restrictive strategies perform significantly better (it has to be considered that due to the logarithmic scale even small differences in Figure 4 for more than 90% load correspond to a large number of affected wavelength channels). The reason can be found in the behaviour of the resulting path lengths versus the offered network load.

Figure 5 gives an example for three strategies applied in a network with 100% conversion. With increasing load, the mean number of links (i. e. hops) per connection is reduced for FSR because longer connection requests 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 total network blocking. This is particularly apparent for the ADR strategy which dynamically searches in the whole network for a free path.

These results lead to the conclusion that to achieve good routing performance

over the whole load range a component is required which considers some kind of path length limitations. The next subsection presents several approaches.

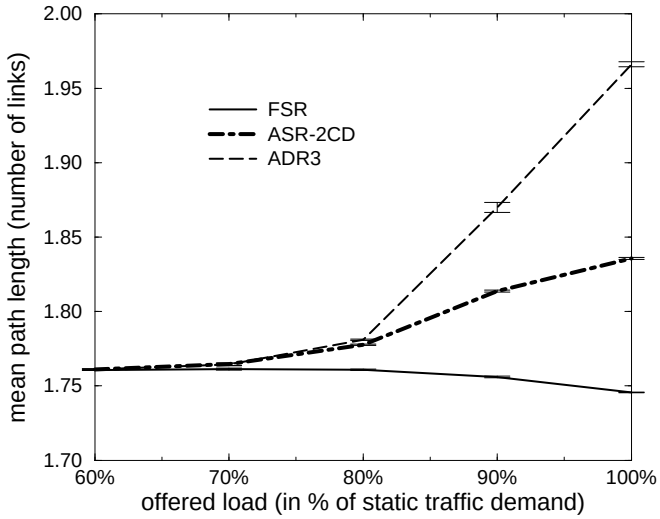

Figure 5: Path lengths for different routing strategies and network load values

3.2 Influence of length limit strategies

To consider path length limits within a routing strategy, it has to be defined first which measure is taken to describe the "length" of a wavelength path. This measure could be the geographical length expressed in meters, the number of regenerators or amplifiers passed, or the number of nodes a wavelength channel has to pass. While the first two measures refer more to physical aspects of a wavelength path, the latter is more related to the required network resources. We choose a similar measure for our investigations: the path length is expressed using the *number of hops* (i. e. the *number of links*) of a path.

Limitation Strategies

We investigated several possibilities for limiting path lengths. The most simple approach is applying a length limit based on absolute values (e. g. not allowing paths longer than *n* hops). However, this has a severe drawback since it leads to an unfair limitation of long-distance requests. Another drawback occurs for large networks: *n* has to be chosen big enough to fulfil the longest possible connection request (i. e. a request between the node pair with the largest distance). But on the other hand, this would allow rather long alternatives for nodes with a very short distance.

An improvement is to choose a *relative length limit* which considers the length of the shortest path serving as a first alternative. After a detailed investigation of the network topology and the connection pattern, we developed the following

relative length limit. The length of an alternative route is limited to k_i times the original length of path i. k_i itself depends on the number of hops for the shortest path and increases with the shortest path length. Thus, we have a variable relative length limit. For example, for shortest paths with one hop, we allow alternative routes with three hops ($k_1 = 3$), while for a shortest path length of three hops we allow alternatives with four hops ($k_3 = 1.33$).

Results

Figure 6 shows the performance of this approach for a strategy using three pre-calculated biased paths with a dynamic calculation in addition (*ADR3, relative limit*) for a network with 100% conversion. Compared to ADR3 without any limit, the performance using a relative limit is better for high load, but for low load blocking is increased due to unnecessary restrictions for the routing process.

To reduce this effect, an adaptive length limit was introduced, which applies the length limit dependent on the link loads. A limitation is only considered for links which are loaded above a certain threshold (e. g. 95% for the results in Figure 6). The results - depicted with a thick dashed line - show that this strategy is very close to the achievable optimum over the whole load range.

Thus, the most promising routing approach to achieve good network performance independent of the load has to comprise several elements: it should prefer routes "biased" according the static network planning, provide a selection between various "good" alternatives, allow a dynamic calculation for cases where all alternatives are blocked, and finally consider adaptive (i. e. dependent on the network load) and relative (i. e. dependent on the node distance) path length limits.

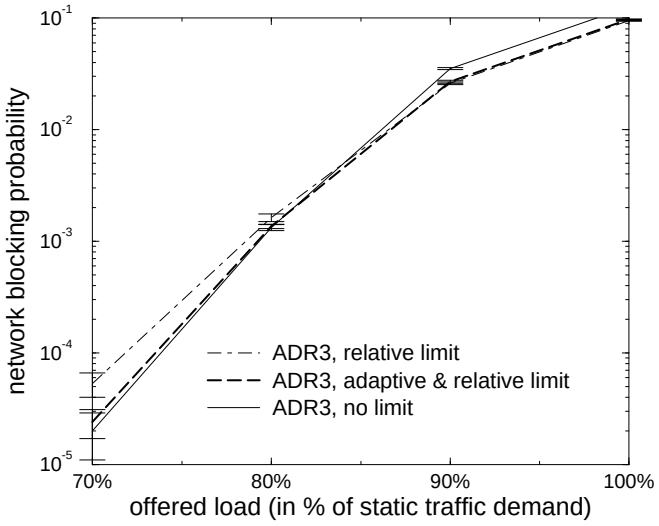

Figure 6: Influence of different path length limitation strategies

4 Influence of Poisson and non-Poisson traffic characteristics

Most investigations of WDM networks reported in literature are based on the assumption of Poisson traffic. The approximation of real network traffic with Poisson traffic has been proven to be a good approximation for many classical networks in the past. And although recently many complicated but more accurate traffic models were developed, the simplification made by using Poisson traffic turned out to be helpful and sufficiently accurate in many cases. However, it is not clear at all how traffic in future WDM networks will behave. Therefore, the question how the routing strategies will behave under non-Poisson traffic is important and getting increasing interest in research work.

In [9] this question was studied for hop-by-hop routing strategies whereas in the following we concentrate on central strategies. We generate non-Poisson traffic by varying the coefficient of variation (CoV) for the interarrival and the call holding times, respectively. A $CoV = 1$ results in a negative-exponential distribution for the time variable, for $CoV < 1$ we get hypo-exponential and for $CoV > 1$ hyper-exponential time distributions.

Influence of call holding time (service time) behaviour

Figure 7 shows the influence of the call holding time (i. e. service time) characteristics under the assumption of negative-exponentially distributed interarrival times, i. e. the call arrival process is Poisson. It can be seen that in this case the holding time CoV has almost no influence on the network performance although we vary the CoV between 0 (corresponding to deterministic holding times) and 10 (corresponding to a very high variance). The figure shows that this holds for a network without converters as well as for a network with full conversion capability. Moreover, the difference between the two conversion strategies is much more significant than between different CoV values.

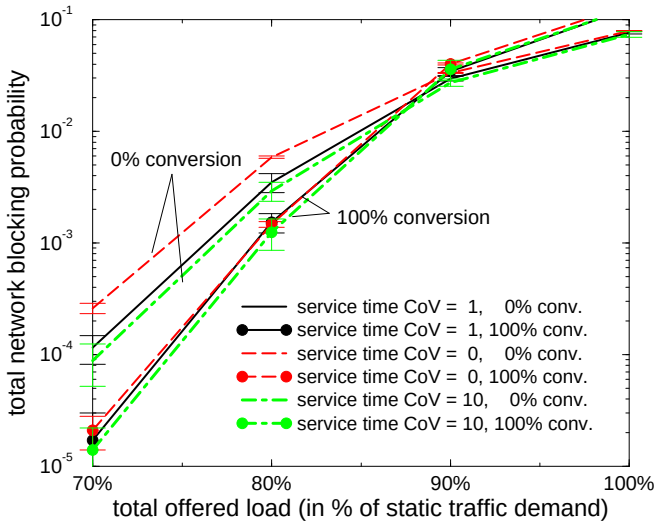

Figure 7: Influence of service time characteristics for a Poisson arrival process

Influence of call interarrival time behaviour

The results are completely different if the interarrival time CoV is varied while the call holding times are negative-exponentially distributed. Figure 8 shows a strong influence of the interarrival time CoV. For $CoV > 1$ we get higher, for $CoV < 1$ we get lower blocking probabilities compared to $CoV = 1$. This influence is much more significant than the difference between no, partial and full conversion capabilities.

We also investigated cases where both, interarrival and holding times are non-Poisson. In these cases, also the variation of the holding time CoV gets an important influence.

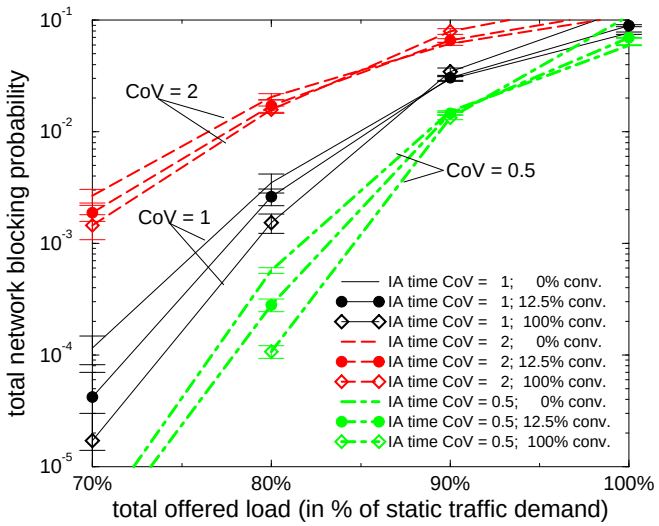

Figure 8: Influence of interarrival time characteristics for negative-exponential call holding times

5 Conclusions and Outlook

This paper dealt with the performance of WDM cross-connected networks under dynamic traffic conditions. The influence of various parameters on the routing strategy was investigated. It was shown that several parameters derived from the network topology have a strong impact on routing performance. Different routing strategies were developed and investigated, showing that a new strategy based on multiple "biased" alternatives, dynamic path search, and an adaptive length limit achieves good performance over the whole load range. Additionally, the influence of traffic characteristics was investigated. The strong influence of the call interarrival behaviour was shown. Moreover, it was shown that the call holding time behaviour has almost no influence on the routing performance, but this holds only for Poisson interarrivals. Further work will include other node and network architectures (e. g. ring networks based on ADMs) and the impact of protection and restoration strategies on the routing process.

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References

[1] A. Adas: "Traffic models in broadband networks", *IEEE Communication Magazine*, Vol. 35, No. 7, July 1997, pp. 82 – 89

[2] G. Ash: *Dynamic routing in telecommunications networks*, McGraw-Hill Telecommunications, 1997

[3] A. Girard: *Routing and dimensioning in circuit-switched networks*, Addison-Wesley, 1990

[4] E. Karasan, E. Ayanoglu: "Effects of wavelength routing and selection algorithms on wavelength conversion gain in WDM optical networks", *IEEE/ACM Transactions on Networking*, Vol. 6, No. 2, April 1998, pp. 186 –196

[5] A. Mokhtar, M. Azizoglu: "Adaptive wavelength routing in all-optical networks", *IEEE/ACM Transactions on Networking*, Vol. 6, No. 2, April 1998, pp. 197 –206

[6] W. Van Parys, B. Van Caenegem, P. Demeester: "Reduction of blocking in arbitrary meshed WDM networks through a biased routing approach", *Proceedings of the OFC '98*, February 1998, p. 94

[7] J. Späth, S. Bodamer: "Performance evaluation of photonic networks under dynamic traffic conditions", *Proceedings of the 2nd IFIP TC 6 Working-Conference on "Optical Network Design and Modelling"*, February 1998, pp. 15 – 19

[8] J. Späth, S. Bodamer: "Routing strategies for photonic networks under dynamic traffic conditions", *Proceedings of Networks and Optical Communication (NOC) '98*, June 1998, pp. 174 – 177

[9] J. Späth, S. Bodamer: "Routing of dynamic Poisson and non-Poisson traffic in WDM networks with limited wavelength conversion", *Proceedings of the 24th European Conference on Optical Communication (ECOC) '98*, September 1998, pp. 359 – 360