Design and Dimensioning Aspects of Photonic Transport Networks

Jan Späth
Institute of Communications Switching and Data Technics
University of Stuttgart, Seidenstr. 36, D-70174 Stuttgart, Germany
Phone: +49 711 121 2488 Fax: +49 711 121 2477 E-mail: spaeth@ind.uni-stuttgart.de

Abstract. *It is expected that photonic networks will be used to realise future transport networks due to the high transmission capacities of optical fibers and the promising prospects of optical switching techniques. This work gives an overview of different architectures for photonic networks and investigates various important design and planning aspects such as for example technological constraints or routing strategies. Moreover, the architecture of network nodes will have a significant influence on network performance. Therefore, the paper includes a comparison of nodes with optical cross-connect functionality focusing on different concepts for sharing wavelength converters among multiple connections. Sharing is economically advantageous due to the difficult realisation of converters. Performance models for photonic cross-connects are developed and analysed.*

The results show that, in general, wavelength converters increase node performance significantly due to the fact that wavelength conflicts can be avoided. However, at a certain degree of converter employment, additional converters result in almost no further performance improvement. Therefore, the results may be helpful for dimensioning cross-connects with regard to converters.

1 Introduction

Photonic networks will gain more importance in the future owing to specific advantages of optical technologies such as high transmission capacities or transparency of optical channels. These networks can be classified into the two groups single-hop and multi-hop networks.

In single-hop networks all signals are transported from source to destination without any opto-electronic conversion. This can be realised for example with Passive Optical Networks (PONs) based on a star coupler and either tunable senders and fixed receivers or fixed senders and tunable receivers. Mainly, such networks will be applied in the access area.

Multi-hop networks contain at least one opto-electronic conversion between source and destination. This allows a flexible logical network topology assignment to any physical topology. Moreover, the number of nodes and the network extension can be increased significantly compared to single-hop solutions, so that most wide area networks will be based on a multi-hop scheme.

Apart from access networks, wide area transport networks are expected to be another application area in which an effective use of photonic technology will be possible. As already worked out [Sato94], a future transport network will comprise several layers: an optical layer serving as transport layer with an enormous bandwidth already today which will significantly increase by future use of WDM (Wavelength Division Multiplexing), and an electrical layer. Additionally, each of these two layers may provide paths or virtual paths.

In general, a layered network architecture enhances the network functionality in terms of flexibility and reliability by supporting the combination of multiple connections of a higher layer into one lower level group and providing additional protection and restoration facilities [Brac93, Sato94]. Moreover, a layered structure allows to migrate from the existing electrical to the future transport network. Step by step a photonic core network may be added retaining existing equipment.

As photonic networks represent large investments and failures may have disastrous consequences a careful planning and design process is required. Network elements must be arranged and dimensioned according to traffic requirements and Quality of Service (QoS) parameters while considering various constraints given for example by WDM technology or network infrastructure.

In the last years, rapid progress in technological research has enabled the development of optical nodes but some problems still remain. [Hill93] discusses critical elements for switching subsystems, e.g. tunable filters and space switching elements. [Joha93] outlines problems with the realisation of key elements such as optical amplifiers or wavelength selective devices.

Two of the most crucial elements which have severe impact on the architecture and the performance of photonic networks are wavelength converters and signal regenerators [Alex93, Hube94]. Therefore, besides future technological research activities, performance evaluations are required to assess the proposed network architectures and to give guidelines for further research activities.

The rest of this paper is organised as follows. The following section gives a short summary of some planning and design aspects. It turnes out that the architecture and performance of network nodes is a substantial aspect for planning a photonic network. Therefore, Section 3 briefly presents the functional and QoS requirements for photonic nodes. Then, several architectures for optical cross-connects which are supposed to be the most important kind of nodes in photonic transport networks are discussed and qualitatively compared. Section 4 contains the performance modelling. The performance evaluation

is presented in Section 5 and discussed in Section 6. Finally, some conclusions will be drawn.

2 Planning and Design Aspects

2.1 Technological Constraints

For the planning of photonic networks, technology constraints play an even more decisive role than for electrical network planning due to the less mature technology. Whereas fibre technology has already reached a relatively stable state, there exist a lot of unsolved questions concerning node components such as switching elements, (de-)multiplexers, lasers, receivers, regenerators or wavelength converters. However, for some components promising results have already been achieved or are expected in the near future.

2.2 Traffic Handling

A major planning aspect is the expected network traffic since the planning process should lead to an optimised network which fulfils all traffic requirements at a minimum of costs. In general, traffic requirements are given in terms of bitrates.

In a photonic network these bit streams can be assigned to wavelengths in various ways which can be divided in two categories: (1) assigning optical channels for each single connection and (2) grouping strategies which cover multiple connections. The second method can be further extended by permitting a rearrangement of some traffic flows (see Figure 1). This will allow the most efficient use of wavelengths but it will also lead to a large number of combinations which have to be investigated. Therefore, a restriction on some special cases seems to be inevitable for any planning process.

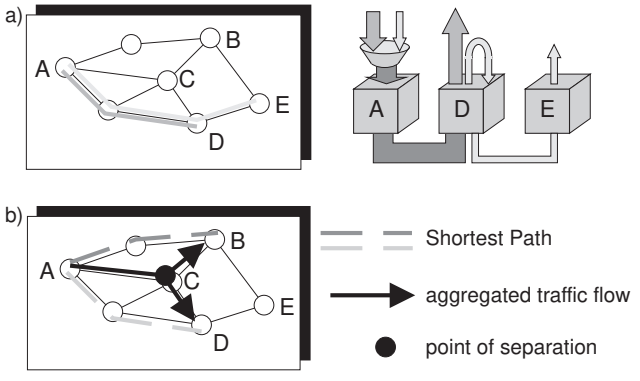


Figure 1: Example for assigning traffic flows to wavelenghts: a) combination on commonly used links, b) rearrangements of traffic flows

2.3 Routing

In WDM networks, routing comprises additionally to the classical task of finding a valid route from source to destination the task of assigning suitable wavelengths to the optical channels. Routing strategies can optimise various parameters. Two main groups can be distinguished. First, it is possible to minimise the total length of all connections in the network by choosing for each connection the shortest path allowed by the ducts. Second, the total length of used fibres in the network may be minimised. In general, this will lead to longer connections but to fibres utilised with a higher percentage.

2.4 Resource Distribution

Two resource elements of photonic networks are wavelength converters and 3R-regenerators (Repeating, Reshaping, Retiming). Currently, both are very expensive and difficult to realise. An important feature is that these resource elements can be located at various places (e.g. nodes). For example, the locations of regenerators can be varied along a connection as long as the maximum regenerator distance is not exceeded. Sharing some regenerators among the connections passing a node can be useful since only long-distance connections need regenerators.

There exist various resource arrangement strategies ranging from distributing resources uniformly in a network up to centralised solutions with concentrating resources in pools as far as possible. A planning process has to reckon with the strong correlation between efficiency and complexity of the different strategies.

2.5 Cost Function

An essential part of a planning process is an appropriate cost function which allows to compare different network variants. Such a cost function should consider all constraints and allow the weighting of different parameters as for example QoS aspects or the number of required components. Moreover, the cost function has to take into account the various parameter interdependencies.

3 Architecture of Future Photonic Network Nodes

3.1 Node Requirements

In the past, first ideas to realise a photonic node were based on optical/electrical transformation and switching in the electrical domain [Nish91]. But since significant parts of the traffic are only relayed by a network node without any further signal processing, it was proposed to offer pure optical switching without transformation into the electrical domain for some channels (i.e. wavelengths) [Naka91]. Then, nodes were suggested using polarisation independent, pure optical switching without wavelength conversion [Sawa92].

Meanwhile, the list of desired properties for photonic network nodes has lengthened and includes a lot of sometimes even contradictory requirements:

- Higher node throughput rates by using all-optical switching techniques instead of electrical switching
- Switching of a single wavelength out of the set of wavelengths transported in WDM mode on one fibre
- Switching of the aggregate signal of a fibre without dividing up the light into single wavelengths for fast protection switching
- Adding and extracting local optical / electrical signals to and from the signal stream at a node, respectively
- Transforming optical signals into the electrical domain for further signal processing
- Providing an economic alternative to electrical nodes with comparable performance while offering a high QoS

Blocking probability is one important QoS aspect. In optical networks based on the WDM scheme, wavelength conflicts on a fibre resulting in blocked connections may occur if it is tried to switch the same wavelength from two input fibres of a node to one outgoing fibre. To reduce this blocking probability, wavelength converters can be used to change signals from any incoming to an arbitrary outgoing wavelength. Moreover, network nodes should have a small impact on signal quality requiring some sort of signal regeneration.

As mentioned above, basic components of a photonic cross-connect (CC) are wavelength converters and signal regenerators which are still expensive and difficult to realise. Therefore, the idea is to use pool concepts for hybrid nodes, i.e. these nodes will only be partially equipped with wavelength converters or regenerators [Lee93]. If the cost situation changes significantly in the future, there may be one converter and one regenerator for each wavelength used in a node [Sato94]. Then, wavelength conflicts can be avoided and the well-known conditions for non-blocking switching networks are valid.

3.2 Cross-Connect Architectures

The central element of a photonic cross-connect will be a switching network comprising two basic blocks: a space division switch and a wavelength division switch (see Figure 2). λ_1 to λ_N denote the various wavelengths on a fibre. The cross-connect architecture can be extended by a time division switch. But owing to the fact that no convincing all-optical realisations for a time division switch are yet known, such architectures will not be considered in the following.

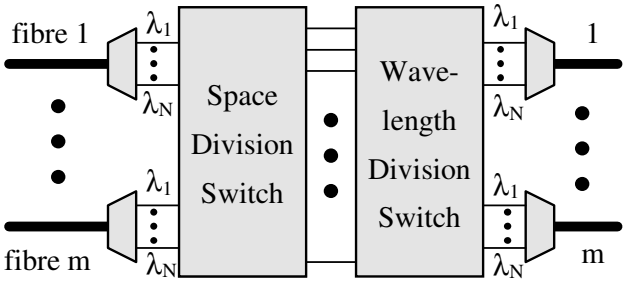


Figure 2: Generic cross-connect architecture

Four basic WDM switch types can be distinguished considering the possible combinations of converter and regenerator employment. In particular, for both resource elements the architectures can be refined by using the degree of sharing resources as a distinctive feature. The one extreme is a complete local use, i.e. one element for each channel is provided. The other extreme is a complete global use, i.e. the resources are shared by the whole network. This leads to a classification according to the following five level hierarchy.

- CCs with one element per channel
- CCs with a pool for each fibre
- CCs with a pool for each link with multiple fibres connecting the same nodes
- CCs with one single pool of elements for the entire CC
- A pool of elements shared by multiple CCs or even the entire network

It would be most efficient to share the resources in a pool for the entire network. However, this concept has the serious drawback of requiring significant management efforts to control these pools. Moreover, physical constraints must be considered, e.g. sharing regenerators for a network is limited by the maximum regenerator distance. Thus, this concept is only applicable in rather small networks and will not be pursued in the following.

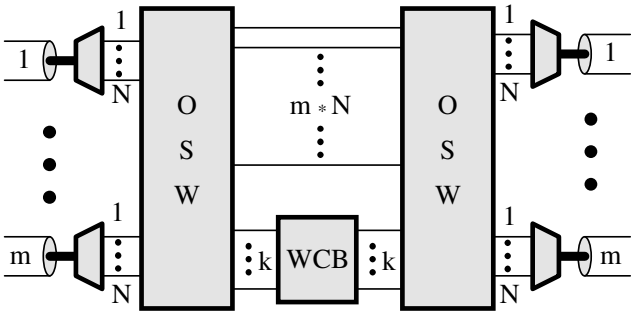
The pool concepts described here are valid for all kinds of resources which can be shared by multiple channels, such as converters or regenerators. But since the throughput performance of a CC is mainly influenced by the number of converters and not by the number of regenerators, a short qualitative comparison of the differing CC structures is done regarding only converters. Criteria taken into account include costs and the network management effort for nodes of equivalent size.

CCs without wavelength converters result generally in a minimum of hardware costs, since only a small switching network per wavelength is required and none of the expensive converters is used. On the other hand, network management is quite complex. A CC may reject connections even if a non-blocking space division switch is applied due to possible

wavelength conflicts on outgoing fibres. This also complicates the routing of connections because a connection has to be established from the source to the destination via a single continuous wavelength. This is named the "WP concept" [Sato94] and the corresponding nodes are referred to as WP-CCs.

CCs with dedicated converters, i.e. one converter per channel, result generally in a more expensive solution since a maximum use of expensive converters is made. Though, fixed instead of variable converters can be used and a single switching network is sufficient. Furthermore, using a non-blocking switching network simplifies network management due to a non-blocking CC and the capability of assigning wavelengths link-by-link allowing a virtual wavelength path (VWP) concept. Thus, these CCs are referred to as VWP-CCs in the following.

Pool concepts allow a shared use of resources. In general, with an increasing number of channels sharing the same resources, the efficiency is increasing, too. Nevertheless, sharing has also some drawbacks. The CC structures get more complex and the administration efforts grow with the degree of sharing. Figure 3 shows the architecture for a share-per-node concept with *k* converters requiring a higher amount of space division switching elements than VWP- or WP-CCs. Moreover, tunable instead of fixed converters are applied. Similar architectures can be derived for the share-per-link or share-per-fibre concept.



OSW: Optical Switch WCB: Wavelength Converter Bank

Figure 3: Example for a CC architecture with share-per-node pool concept

Each of the above described architectures can be implemented in different ways with respect to the number of ports, the number of (de-)multiplexers, the number and sizes of switching matrices, etc. If one of the CC concepts has been chosen based on planning results, the optimum realisation has to be selected depending on technological possibilities and the number of fibres to be connected to the node.

4 Modelling

In this section, the performance modelling for a single CC based on the following assumptions according to Figure 2 is described. *m* fibres are attached to the input and the output of the CC. A demultiplexer separates the N wavelengths transported in WDM mode on each input fibre. These wavelengths are passing a non-blocking space division switch. Then, depending on the considered pool concept for converters (dedicated converters, share-per-fibre, share-per-link, share-per-node), a wavelength division switch follows as well as a multiplexing stage.

In order to investigate the blocking probability of a CC according to our model it is sufficient to consider outgoing fibres since only there blocking is possible. Blocking can be caused either by a fibre already occupied with a maximum of N channels or by a wavelength collision which cannot be solved due to missing converters. In case of blocking a connection is rejected, i.e. a loss system is considered.

To model the traffic, we assume an infinite number of sources which generate connection requests randomly to any of the nodes of the photonic network. The traffic is supposed to be uniformly distributed, i.e. each destination node is chosen with the same probability. Since no specific routing strategy is applied, these assumptions result in the same probabilities for each outgoing fibre of a network node to be used. Therefore, the *m* outgoing fibres are completely independent besides the fact that the converter pool may be shared amongst them.

Moreover, it is supposed that all of the available wavelengths *w* are used with the same probability. This is due to the assumptions that a sender chooses randomly one of the available wavelengths whenever a connection should be established, and that the signal is converted randomly to a free wavelength if a wavelength conflict occurs and a converter can be used.

These assumptions lead to a Poisson arrival process of connection requests with rate μ for each outgoing fibre of a CC. Furthermore, connection holding times are supposed to be exponentially distributed with mean value ε.

In a real network routing strategies being more sophisticated than the above mentioned random choice will be applied. This will lead to improved performance results, so that blocking calculated according to our assumptions lead to an upper bound for the expected real blocking probabilities.

5 Performance Evaluation

In sequel, the exact analysis for the case of share-per-fibre will be outlined using a two-dimensional Markov chain approach. Additionally, an approxi-

mation for a share-per-link and share-per-node CC is presented.

The number of available wavelengths w is considered as a parameter, since it is possible to decrease blocking probabilities due to wavelength conflicts by having a larger set of wavelengths than channels on a fibre ($w > N$). Let k be the number of converters of the share-per-fibre pool. There will be a certain number of channels using no converters denoted by i, $i \in 0,1,...,N$, and a number of channels using a converter denoted by j, $j \in 0,1,...,k$. Hence, the state space is given by (i,j) with the constraint $i + j \le N$. The traffic assumptions made in section 4 lead to an offered load $A = \mu / \varepsilon$ per fibre.

Figure 4 shows the obtained Markov chain with transition rates. States in which arriving connection requests are blocked due to a full fibre are depicted with two circles. In the states depicted grey blocking occurs only if the wavelength of the incoming connection request is already used, i.e. not all arriving connection requests are blocked.

The analysis of this model leads to a system of linear equations. The equilibrium probabilities $p_{i,j}$ of the states (i,j) can be determined by these equations and

$$\sum_{i=0}^{N} \sum_{\substack{j=0 \\ j \le k}}^{N-i} p_{i,j} = 1 \quad .$$

From $p_{i,j}$ various results can be derived. Blocking caused by wavelength conflicts due to a lack of converters is given by $B_{conv,fiber} = \sum_{i=0}^{N-k-1} p_{i,k} \cdot \frac{i+k}{w}$.

Blocking caused by a completely occupied fibre is given by $B_{full} = \sum_{j=0}^{k} p_{N-j,j}$.

Therefore, the total blocking probability results to

$$B = B_{conv,fiber} + B_{full} \quad .$$

In principle, it would be possible to calculate blocking probabilities exactly for all CC architectures by using a multi-dimensional Markov chain. But due to the large state spaces and the rapidly growing complexity emerging already with simple CC structures, only results for small CCs or for special architectures can be obtained exactly. An exact solution for a share-per-node CC with two fibres was derived using a four-dimensional Markov chain. For larger and more complex CCs, in particular for CCs with any number of fibres and a share-per-node or share-per-link pool concept approximate solutions were developed.

An approximate solution for blocking caused by a lack of converters for CCs with share-per-link or share-per-node (B_{conv}) can be obtained as follows. First, an unlimited number of converters is assumed, i.e. wavelength conflicts cannot occur, and the probability distribution of the number of converters

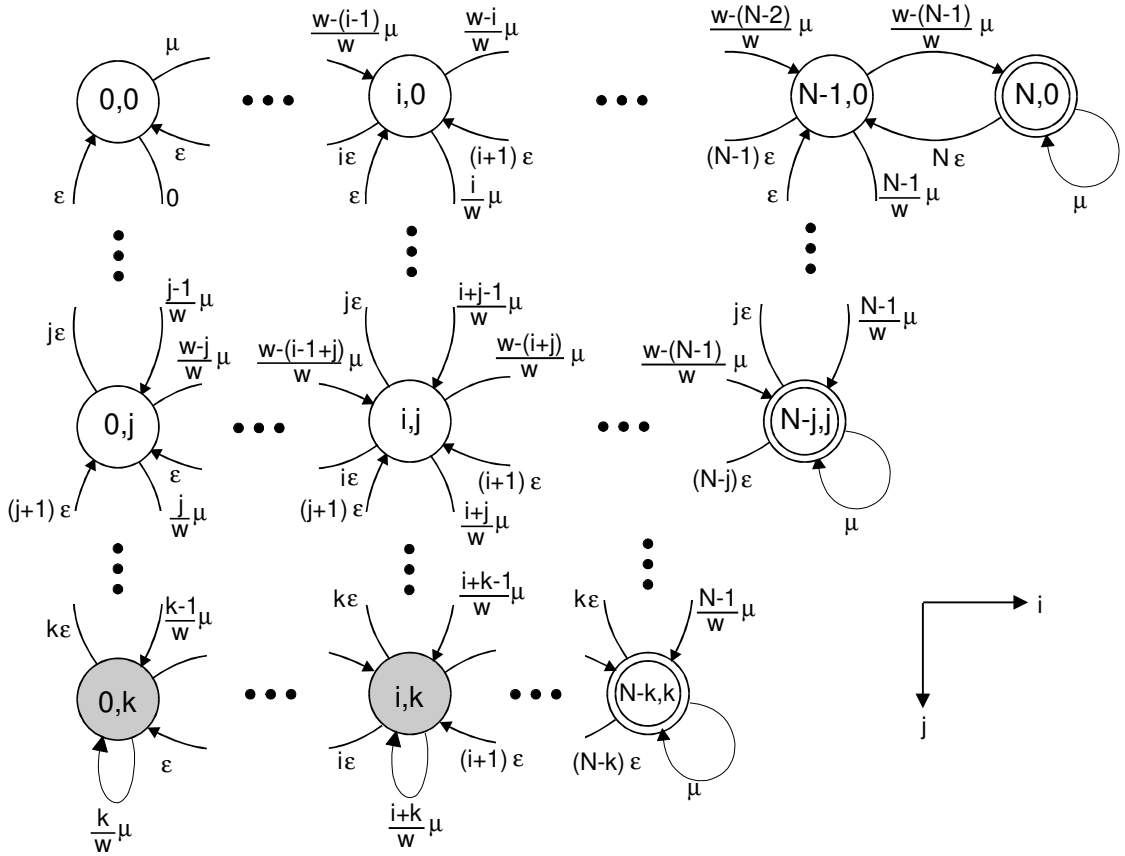


Figure 4: State transition diagram for a share-per-fibre architecture

for a single fibre is calculated. The probability distribution of the total number of converters for all fibres is obtained by a convolution of the single probability distributions. Let $B_{conv,l}$ be the probability that l converters are used by all fibres. Then, B_{conv} is approximated by summing up the probabilities of all states in which the number k of available converters is exceeded:

$$B_{conv} = \sum_{l \geq k} B_{conv,l} \quad .$$

Thus, this approximation represents an upper bound by overestimating the exact results. The approximation was validated by a comparison with the exact analysis for a CC with two attached fibres and a share-per-node concept using a four-dimensional Markov chain.

6 Results

In the following some results are presented to show the impact of the various parameters on the blocking probability of a CC. The number of wavelengths on a single fibre N is set to 8. At present, N in this order of magnitude seems to be realistic, although in some publications much higher numbers are assumed. Furthermore, the number of available wavelengths is chosen equal to the number of channels per fibre ($w = N$).

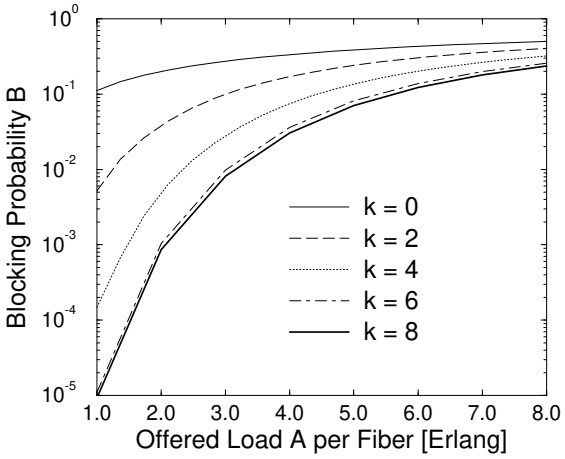


Figure 5: Blocking probability B for a share-per-fibre CC (N = 8, w = 8)

Figure 5 presents the exactly analysed blocking probabilities for a CC with share-per-fibre architecture. The cases $k = 0$ and $k = 8$ represent a WP-CC and a VWP-CC, respectively. The results indicate that using wavelength converters significantly decreases blocking probabilities compared to the case $k = 0$, but it can be also seen that increasing k from 6 to 8 leads only to a marginal improvement.

This can be explained by the fact that the total blocking probability is composed of two parts: (1) all channels on the fibre are used and (2) a required converter is not available, thus a wavelength conflict cannot be solved. The influence of these parts depends mainly on the offered load and on the CC architecture.

Figure 6 shows the blocking probabilities for a share-per-node CC with $m = 8$ fibres, each fibre carrying $N = 8$ wavelengths in parallel resulting in a total of 64 channels. It is assumed that CC sizes in this order of magnitude will be realistic. The two solid lines for $k = 0$ and $k = 64$ represent a WP-CC and VWP-CC, respectively. These values were derived by an exact analysis and they enclose the area of blocking probabilities for any pool concept.

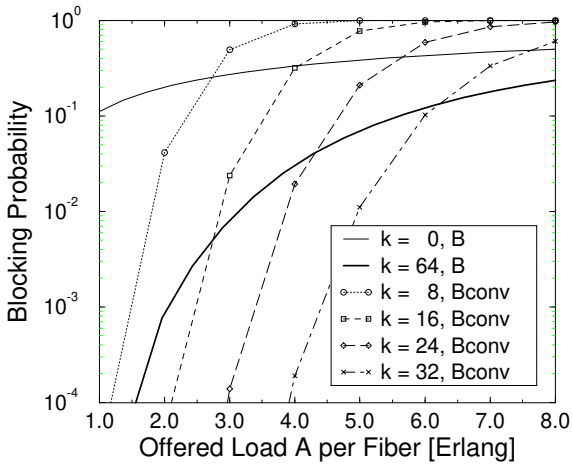


Figure 6: Total blocking probability B and approximate blocking probability due to wavelength conflicts B_{conv} (m = 8, N = 8, w = 8)

The chosen approximation (dashed lines in Figure 6) overestimates the exact values for B_{conv} as explained in the previous section. It allows to define areas in which the number of converters considering a given load has almost no influence on B. The minimal total blocking which is achieved by using one converter per channel is depicted by the line for B with k = 64. The total blocking probability improvement by offering additional expensive converters is negligible while B_{conv} is below this lower bound.

As an example it is assumed that an offered load up to 4.5 Erlang per fibre should result in a maximum of $B = 5\%$. Figure 5 shows, that increasing the number of converters over 24 would only lead to negligible further improvements of B. The overestimated approximation of B_{conv} is already below the minimal total blocking, which is depicted by B with $k = 64$.

If the number of channels per fibre is increased while providing one converter per channel ($k = N$, i.e. there are no wavelength conflicts) the blocking

probability will decrease for a certain load per channel according to the economy of scale. An improvement for all loads can still be seen if the ratio N / k is kept constant (Figure 7).

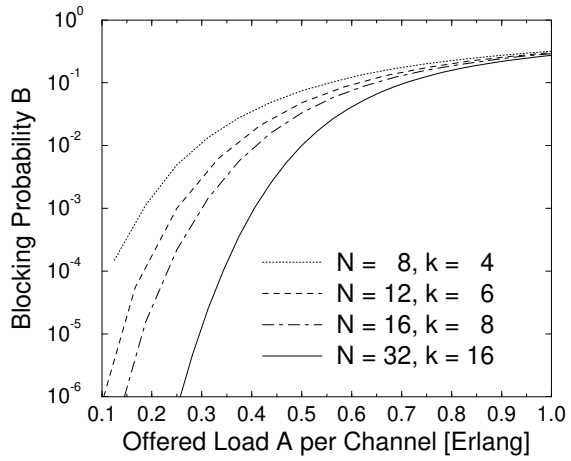


Figure 7: Blocking probability for a share-per-fibre CC with $N / k = 2 = const$ ($w = N$)

The situation changes if the number of converters and the offered load per wavelength are kept constant ($k = \text{const}$, $A = \text{const}$) while increasing the total number of channels N per fibre (Figure 8).

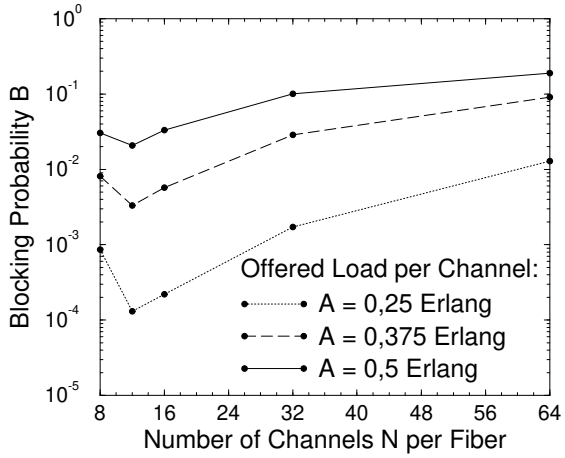


Figure 8: Blocking probability for a share-per-fibre CC with $k = 8 = const$ and $w = N$

At low N, B decreases with increasing N as would be expected according to the economy of scale. Then, a minimum of B is achieved and with further increasing N, B increases too. This can be explained by the different influence of the two parts $B_{conv,\,fibre}$ and B_{full} of the total blocking probability. At high N, a lot of channels have to share the available converters. Therefore, lack of converters is getting more and more the limiting factor leading to high values for $B_{conv,\,fibre}$ and as a consequence to high values for B.

7 Conclusions

In this work, some important planning aspects and main characteristics of a photonic transport network architecture based on cross-connects have been presented. A brief comparison of pool concepts for wavelength converters was outlined demonstrating the trade-off between performance improvement and management effort. For the different architectures, a performance evaluation has been carried out comprising exact solutions as well as an approximation. The approximation aims to reduce the computing effort arising from the complexity of cross-connect structures with a large number of attached fibres.

The performance evaluation results indicate that wavelength converters decrease blocking probabilities significantly and thus have an important influence on network behaviour under dynamic traffic conditions. However, at a certain degree of converter employment, additional converters result in almost no further performance improvement. The results may help to dimension nodes considering given constraints. They allow for example to determine the number of converters necessary to achieve a certain blocking probability under a given load and a given number of channels per fibre.

References

[Alex93] S.B. Alexander, R.S. Bondurant, D. Byrne et al.: *"A Precompetitive Consortium on Wide-Band All-Optical Networks"*, Journal of Lightwave Technology, Vol. 11, No. 5/6, May/June 1993, pp. 714-732

[Brac93] C.A. Bracket, A.S. Acampora, J. Sweitzer et al.: *"A Scalable Multiwavelength Multihop Optical Network: A Proposal for Research on All-Optical Networks"*, Journal of Lightwave Technology, Vol. 11, No. 5/6, May/June 1993, pp. 736-752

[Hill93] G.R. Hill, P.J. Chidgey et al.: *"A Transport Network Layer Based on Optical Network Elements"*, Journal of Lightwave Technology, Vol. 11, No. 5/6, May/June '93, pp. 667-676

[Hube94] M.N. Huber, R. Osborne: *"Architecture of an all-optical ring network"*, EFOC&N, June 1994, pp. 102-105

[Joha93] S. Johansson, M. Lindblom, P. Granestrand, B. Lagerström and L. Thylén: *"Optical Cross-Connect System in Broad-Band Networks: System Concept and Demonstrators Description"*, Journal of Lightwave Technology, Vol. 11, No. 5/6, May/June 1993, pp. 688-694

[Lee93] K.-C. Lee and V. Li: *"Routing and Switching in a Wavelength Convertible Optical Network"* , Proceedings of IEEE Infocom 1993, pp. 578-585

[Naka91] T. Nakashima, Y. Hamazumi, N. Tokura and K. Kikuchi: *"Photonic Access Network Architecture"*, Proceedings of Globecom 1991, pp. 602-606

[Nish91] M. Nishio and S. Suzuki: *"WD&MMT Switching Networks in Combination with Photonic and Electronic Switching Technique"*, Proceedings of IEEE ICC 1991, pp. 590-596

[Sato94] K. Sato, S. Okamoto and H. Hadama: *"Network Performance and Integrity Enhancement with Optical Path Layer Technologies"* , IEEE Journal on Selected Areas in Communications, Vol. 12, No. 1, January 1994, pp. 159-170

[Sawa92] T. Sawano, K. Matsuda, S. Suzuki et al.: *"High Capacity Photonic Switching System"*, Proceedings of IEEE ISS, October 1992, pp. 357-361