Objective Function for Planning and Evaluating a WDM-based Photonic Network

Jan Späth
Institute of Communication Networks and Computer Engineering, University of Stuttgart
Pfaffenwaldring 47, D-70569 Stuttgart, Germany
Tel.: +49 711 685 7990, Fax: +49 711 685 7983, E-mail: spaeth@ind.uni-stuttgart.de

Bart van Caenegem
Department of Information Technology, University of Gent - IMEC
Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium
Tel.: +32 9 264 3446, Fax: +32 9 264 3593, E-mail: bart.vancaenegem@intec.rug.ac.be

Abstract

This paper discusses the importance of an objective function for a network planning process and presents some basic components and general aspects of objective functions. Then, specific aspects of an objective function for planning a photonic network such as wavelength conversion, or scalability and flexibility are discussed. Moreover, selected results on multi-layer planning and consideration of dynamic traffic are presented and summarised. Finally, open points are listed which need further work.

1 Introduction

Network planning is an important task for network operators as well as for system providers, on one hand to evaluate and compare different solution approaches, on the other hand to find a solution which fulfils all requirements with a minimum of resources. This is also true for photonic networks where an efficient planning process is especially desirable due to relatively high costs of single network elements and also due to a great variety of different network concepts which have to be compared before a decision for a certain solution can be made.

Figure 1 presents a generic description of a general network planning process. There are many input parameters given for the planning procedure. An important example is a description of possible locations for network nodes and ducts along which nodes can be interconnected. They are often called candidate nodes/links and depend on the availability of locations for a network operator. The traffic matrix describing all traffic demands the planned network has to fulfil is also very important. At least, this is a two-dimensional matrix containing the amount of traffic (given for example in bit/s or in Erlang) which has to be carried between a pair of nodes. For more detailed considerations, this matrix can also be multi-dimensional so that for example multiple service classes or different QoS (Quality of Service) parameters can be considered.

Furthermore, a detailed description of available network elements is required which should contain the element costs and also a description of element features (e.g. functional restrictions). Moreover, there are several aspects on which the planning process can focus on, e.g. time scale (short-term or long-term planning), network layer (physical layer, transport path layer, higher network layer), or geographic area (core network or access network). Related to this is the choice of a certain planning strategy. For example one could aim for a low cost network, or for a 100% protected high quality network, or for any other operator defined goal. Finally, each planning process has to consider various constraints such as physical, technological, or logical limitations.

Taking all these factors into account, a combination of several planning methods is used to develop a network solution (central blocks in Figure 1). The great variety cannot be described in detail here. A few examples are topological design, demand prediction, traffic modelling, routing of traffic flows, or dimensioning of network elements. Usually, not only a *valid* solution that fulfils all requirements is looked for, but the *optimum solution*. However, to be able to define an optimum, a measure is required to compare different proposals. This is done by defining an *objective function* (also called cost function or optimisation function). After a solution is found, often a separate evaluation step is performed in which for example very time consuming investigations are done (such as traffic simulations or performance investigations). The results of this step may lead to the necessity of performing loops including some of the before mentioned steps.

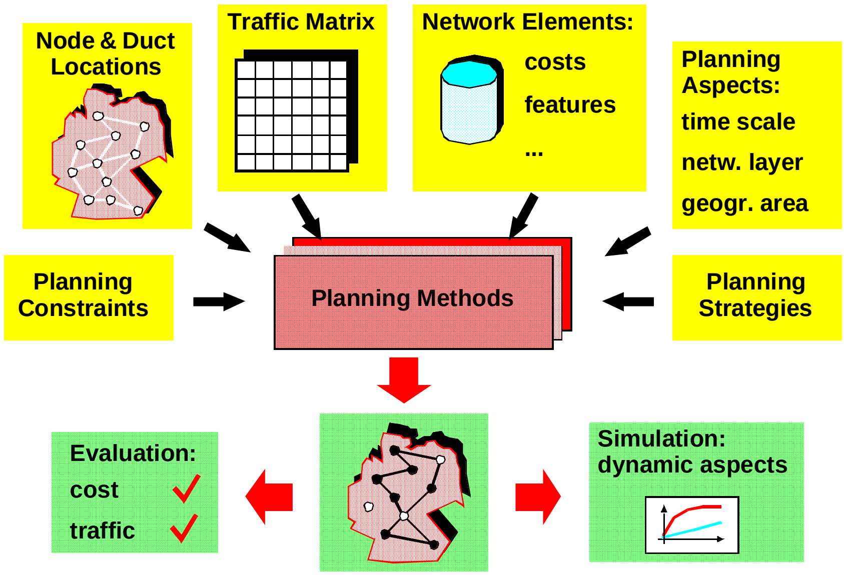

Figure 1: Generic description of a network planning process

One of the central elements of a planning process is the above mentioned objective function which serves as a guideline for all optimisation methods. It allows the comparison of different alternatives according to certain criteria which are represented by the elements of the objective function. These elements need not to be restricted on elements to which "financial costs" can be assigned but may comprise a broader spectrum of aspects. This paper elaborates on various aspects of an objective function.

In Section 2 some basic objective function components are listed. In Section 3, some classification examples and application fields for objective functions are given. While these sections deal with objective functions in general, in Section 4 specific aspects for investigating photonic transport networks are presented. Section 5 presents a short summary and some selected results. Finally, we conclude with a discussion of various open points.

2 Basic Components of an Objective Function

This section gives a short overview on some basic components which could be considered within an objective function for a network design process. Basically, we can distinguish between *financial costs* of the required elements and the *performance* of the achieved network solution covering various functional aspects. These groups are divided further in the following subsections. The listed elements here are not specific for a photonic transport network and as mentioned in Section 1 not only components to which financial costs can be assigned are considered. Moreover, some constraints for a planning process are also mentioned.

The large scope of the list indicates that the importance of the listed elements will strongly depend on the specific planning problem or case study that is considered. Moreover, not all of the aspects listed in the following are easy to describe with quantitative expressions. Therefore, some other strategies to consider these aspects might be necessary. Some examples are given in Section 5.

2.1 Costs of Physical Network Elements

The financial cost of the physical network elements constitute a significant part of the overall network costs. This holds especially for transport networks, where relatively expensive elements are required. Man related working costs for the installation of components (which might be a significant part of the overall costs) can be combined with component costs. The detailed consideration however depends strongly on the specific network technology that is applied. In general, the network elements can be classified into the following groups.

Transmission Systems

This group comprises the cost of all elements required for equipment for point-to-point transmission between nodes. Examples are fibres, copper cables, line amplifiers, or regenerators for either optical or electrical technology.

Switching Systems

This group covers all costs for the network node equipment. Important examples are the switching systems inside the node, control and monitoring equipment, or the port costs for attaching transmission systems. A port may include a multiplexing stage if the switching capacity unit (also denoted *granularity*) is different from the transmission capacity unit. The port cost however, might also be considered within the transmission systems.

The cost model of the switching system and concrete cost parameters strongly depend on the node type. For transport networks, especially cross-connects (CCs) and add/drop multiplexers (ADMs) play an important role. Therefore, specific cost models for different node types might be necessary.

Additional Equipment

Various additional elements are needed for real network operation. Two examples are ducts along which transmission systems can be installed and buildings where node and transmission equipment can be housed. For ducts as well as for buildings restrictions for possible locations may exist and usually only a limited set of *candidate* links or nodes is available for the planning process. For financial cost considerations, it may be necessary to distinguish between buying or leasing resources because the latter results in continuing costs during operation.

2.2 Operation, Administration and Maintenance (OAM)

OAM costs represent a fraction of the overall network costs with an increasing significance. These costs comprise component costs as well as required man power. Especially for OAM costs, the distinction between an *initial part* (mainly components and physical systems needed and training costs) and a *permanent part* (mainly the on-going man related working costs) is useful.

The OAM component costs might be considered together with the above mentioned physical network element costs due to the fact that they arise also at network installation. The man related costs however arise during network operation and therefore the considered time frame has an influence on the total costs. However, considering time-dependent costs within an objective function is rather difficult.

Moreover, these costs are in some way related to the *complexity* of OAM which plays an important role for an efficient network operation. Again, it is very difficult to express this aspect in costs. Therefore other strategies (for example performing detailed evaluations after the planning process) might be required.

2.3 Network Performance

Apart from the costs, the performance of a network is important. In general, there exists a trade-off between cost and performance. A network planning process tries to achieve highest performance with a minimum of cost using various optimisation processes. To describe the network performance different parameters can be used. The following list gives some examples.

Traffic Performance

Traffic performance includes aspects as for example delay, throughput, or losses for signalling as well as for user data. The traffic assumptions on which performance investigations have to be based can be described by many parameters like volume or geographical distribution patterns. An important distinction has to be made between static and dynamic traffic. Static traffic is not restricted to a single fixed value, but can include for example increasing traffic rates or different traffic distribution patterns in the network. The specific feature of dynamic traffic is an inherent random behaviour. In this case, usually dynamic and random variations over time are considered so that additionally to the static traffic parameters also a description of the *behaviour* of the traffic is required. Mostly, this is done by probabilistic distribution functions for certain parameters like call interarrival or call holding times.

The type of traffic depends strongly on the network under investigation. In the transport layer of wide area networks for instance static traffic is dominating, whereas in packet switched local area networks dynamic traffic is mostly filling up the resources.

In many cases however, it is too complex or time consuming to include detailed analytical or simulative investigations into an objective function. Then, post-planning evaluations are required.

Survivability

Survivability usually means the ability of a network to be resilient against outages and is often measured in terms of traffic that survives a link or node failure. Other parameters in this context are *reliability* which is derived from failure probabilities of components or systems, and *availability* which is described by time spans in which a system is either operating or out of order. Based on these two phases various other availability descriptors can be derived [Bare_92].

Survivability describes a network property with increasing importance for the transport layer due to higher bit rates handled by single network elements. Many different techniques exist to achieve survivable networks [John_96]. In [Nede_97] some classification criteria are listed: restoration topology (point-to-point, ring, mesh), restoration control (centralised, distributed), restoration domain (link, path), capacity allocation (dedicated, shared), capacity usage (pre-planned, dynamic). This list – which could be easily extended – shows the great variety of aspects playing a role.

From a network planning point of view, we can distinguish two basic aspects: on the one hand, the "level of survivability", i.e., how survivable a network is, on the other hand the costs for the network elements required to achieve this survivability (*spare elements*). The latter one can be considered together with the costs for working elements.

However, it is much more difficult to determine the "goodness" of a network solution with respect to fulfilling survivability requirements. An overview of literature dealing with this aspect and a description of various survivability measures can be found in [Moit_97]. Most of the measures presented in that paper are *worst case* or *average* values for the amount of traffic that either survives a failure or that is lost. By introducing additional "weighting factors" it is possible to give the traffic on some links a higher priority.

Functionality

Various features describe the performance of a network from a functional point of view. Important examples are the scalability and the flexibility of a network with respect to future changes of the input parameters. In the following, we combine these aspects using the expression "future proof" feature. This feature comprises many aspects such as handling increasing traffic demands, coping with changes in traffic patterns or characteristics, increasing the network size in number of nodes and links, or adding new services.

Although this feature is of great interest for all network operators, it is very difficult to find quantitative measures which allow an inclusion into the objective function. In many cases, it seems to be more promising to adopt specific design rules during the planning process.

2.4 Consideration of Constraints for the Planning Process

Apart from cost or performance issues, a planning process also has to consider several constraints. Some of them can be classified as "hard constraints" which have to be fulfilled. This can be done by either applying appropriate design rules or by performing post-planning evaluations. Other restrictions might be violated but then lead to solutions with lower quality (i.e., higher costs or lower performance). In principle, such constraints could be handled by an objective function. In the following, we try to classify possible planning constraints.

Physical and Technological Constraints

Physical constraints describe the limitations given by physics. These limits will be fixed for the foreseeable future and in this way give some kind of border line for realisations. Examples are the speed of light or the attenuation of certain materials. Technological constraints describe the limits given by a concrete realisation. They are more temporary due to the rapid progress in technology.

Strategical and Other Constraints

Some restrictions for the planning process may also be given by operator strategies. Examples could be the use of a certain technology or the preference for a certain network architecture or topology. Moreover, there might exist political or regulatory rules leading also to constraints for a planning process.

3 Classification of Objective Functions

As indicated in the previous section by the variety of elements, many different objective functions can be applied for network planning. This section gives two classification examples although objective functions could also be classified according to many other criteria.

Application Field: Planning or Evaluation

A comprehensive planning process can be divided into several phases and different objective functions can be applied in different phases. An example is given in Figure 2 where the following phases are distinguished:

- In the *pre-planning phase* various basic decisions are made, such as the choice of node or network architecture, survivability strategy, or traffic parameters.
- The *planning phase* is the main constructive phase where a network solution is designed considering the given input data and constraints. Due to the complexity of this phase, it can be divided into sub-phases. In the figure, an example with four sub-phases is given: topology design, traffic routing, dimensioning, and spare capacity allocation (which includes an additional dimensioning). Several of them can be considered together as long as it is tractable to solve.

  The problems dealt with in this phase all lead to a very high algorithmic complexity. In most cases, a very simplified objective function has to be taken into account to restrict the required computing time. Complex evaluations like discrete event simulations for dynamic traffic investigations are usually not possible in this phase.
- Therefore, a *post-planning evaluation phase* is introduced in which a more accurate and time consuming evaluation of several aspects can be performed.

The whole process can be carried out iteratively so that results of one phase can be used by other phases to improve the final solution.

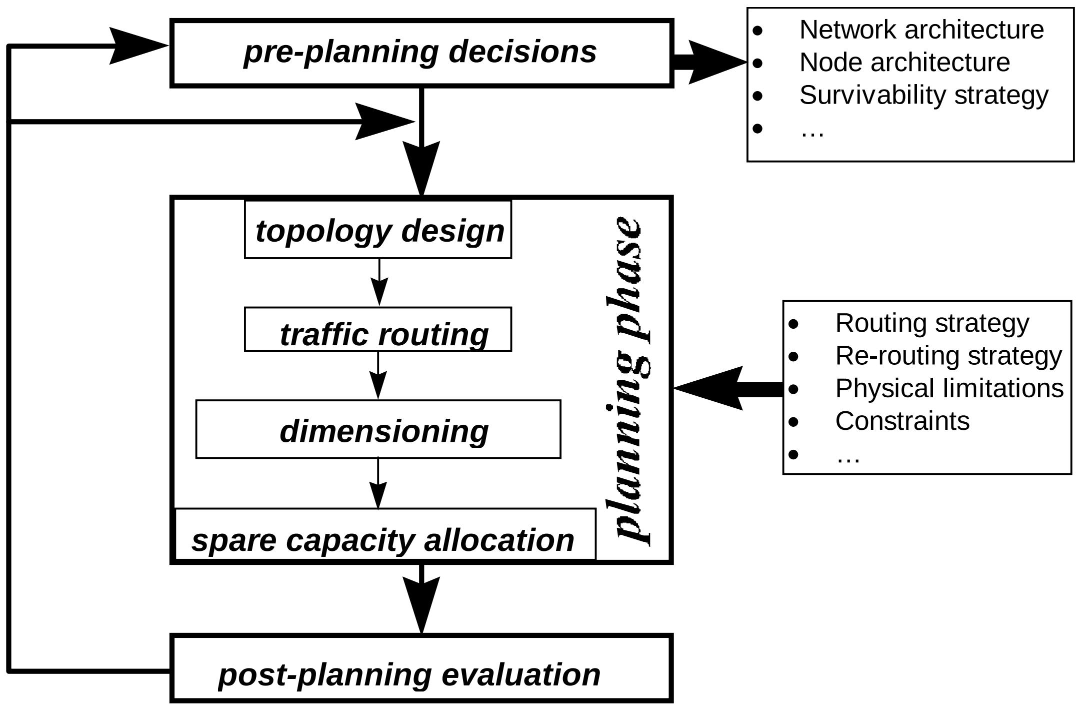

Figure 2: Phases of a planning process

Linear and Non-linear Objective Functions

This classification scheme is based on the mathematical property of *linearity* to classify objective functions. Whether an objective function is of linear or non-linear type plays an important role for planning because it has a fundamental impact on the planning techniques that can be applied. Especially if the objective function is of non-linear type, the whole class of linear optimisation techniques (*linear programming*) cannot be used. These linear techniques however provide several advantages such as run time advantages, tool support, and the possibility of deriving exact solutions. However, a big drawback is that to achieve a linear problem, not only the objective function has to be linear, but also all the constraints: already one single non-linear constraint prohibits the usage of a linear programming technique.

In contrast, for non-linear optimisation techniques no fundamental restrictions exist for the objective function or the constraints so that in principle all problem types can be handled. Well known non-linear techniques are the *non-deterministic search techniques* such as Simulated Annealing or Evolutionary Algorithms. Some drawbacks of these techniques are however the high run time requirements and the fact that no guarantee for finding the optimal solution within finite time can be given.

4 Specific Aspects of Objective Functions for Photonic Networks

In this section we describe some specific aspects for an objective function for planning a photonic network. Some of these aspects were already mentioned in general before and are now described in more detail. Other aspects are more specific for photonic networks and introduced here.

Physical Network Elements for a WDM Transport Network

For a WDM transport network, also transmission equipment (cables, fibres, amplifiers, regenerators, (de-)multiplexers) and switching equipment (ports, switching systems, node internal amplifiers and regenerators) is necessary. The mentioned elements have more or less equivalents in classical electronic networks although there are differences when looking to the details (for example usually the cost values and the handled bit rates per component are higher).

However, there are some elements which are specific for photonic networks. One aspect with big impact on the planning process is *wavelength conversion* described in more detail in the next paragraph.

Wavelength Conversion

Wavelength conversion leads to a higher network flexibility by providing the same functionality in photonic networks as time slot interchange does in TDM networks. On the other hand, wavelength conversion also requires a totally new technology, causes significant costs, and it is still not clear how big the benefits for photonic networks are. Moreover, most conversion techniques known so far suffer from severe negative signal influences such as signal attenuation or noise addition. The subject can be considered on three levels:

- *component level*: isolated consideration of wavelength converter realisations
- *node level*: influence on the node architecture and performance
- *network level*: influence on networking aspects

Component level

To realise wavelength conversion, several techniques exist. In [Stub_96] an overview is given which distinguishes between opto-electronic converters, laser converters, coherent converters, and converters based on optically controlled gates with the two sub-groups cross gain modulation (XGM) and cross phase modulation (XPM). Each of these techniques has its advantages and disadvantages and differences exist when looking to parameters such as insertion loss, noise accumulation, cascadability, realisation complexity, system costs, maximum bit rate, ...

On the one hand, the choice of conversion technique has an influence on the objective function due to different efforts (and therefore costs) required for the solutions. On the other hand, there may also exist an influence on the functionality of the nodes or networks described in the following.

Node level

The application of wavelength conversion will have a strong influence on the realisation of network nodes. We can distinguish nodes according to the amount of wavelength conversion available in the node. This classification can be done using the following parameters (see Figure 3):

- number of converters in the node,
- reachability of converters in case that only a limited number is available (in literature, various different pool concepts for a shared use of converters are proposed; this aspect is related to the connectivity of the switching system inside the node),
- conversion spectrum of a converter.

While the node performance increases with the conversion capabilities, also the costs of a node are increasing. Therefore, an optimisation is desirable reducing the number of converters to a minimum while still fulfilling all requirements. Moreover, this leads also to preferring scaleable node architectures which can be equipped step by step with converters as necessary.

The physical properties of the chosen conversion technique influence also the requirements for other node functionality such as amplification or regeneration inside the node. This again influences the architecture and the costs of a node.

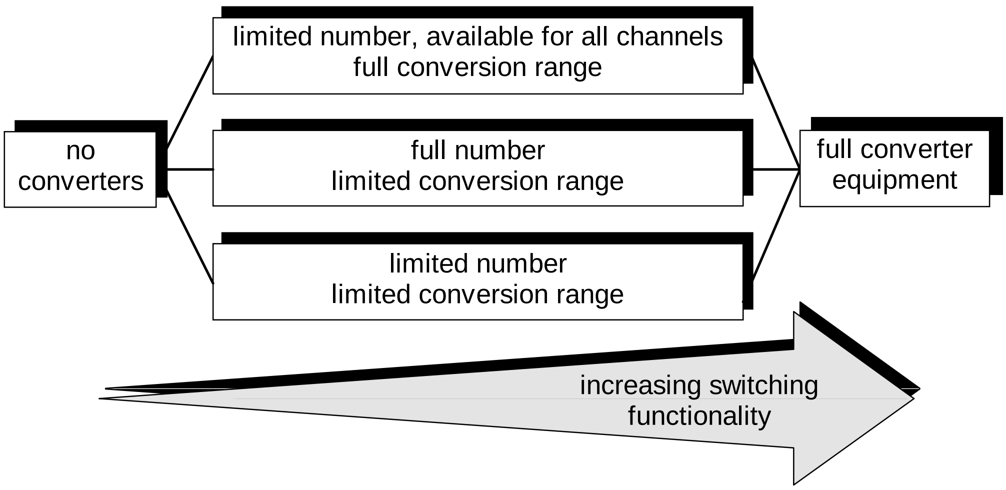

Figure 3: Levels of converter equipment in nodes

Network level

The decision for a certain conversion technique and realisation approach for the node architecture influences also network aspects. This may result either in additional components of an objective function, in specific planning strategies, or in additional planning constraints. Such constraints are restricted conversion capability, limited cascadability of network nodes or maximum path lengths, both due to signal degradation.

First, this may influence the functionality of a network, especially with respect to the performance of routing strategies. This holds for routing and wavelength assignment methods for the planning phase (static assumptions) as well as for the operation phase (dynamic traffic). Moreover, the presence or absence of conversion will also influence internetworking aspects because of the different flexibility at the optical network borders.

Second, an influence exists on the network architecture, topology, and dimensioning and therefore on the costs. Moreover, we see here complex relationships between these parameters and the functionality. A given functionality can be achieved with various solutions (i.e., architectures or topologies) and maybe differing costs. On the other hand, if the costs are given, different solutions may end up with different functionality.

Finally, the limited wavelength conversion capabilities shortly mentioned at the node level exist in similar ways on the network level. Variable parameters are again location of converters, number of converters, and conversion range. We can think of networks in which only a few nodes are equipped with converters or in which all nodes have a restricted number of converters. In combination with the conversion range, many different solutions are possible.

Multi-Layer Network Aspects

For photonic networks, the consideration of multi-layer aspects gets increasing importance:

- Photonic transport networks will be built by extending existing networks with an optical layer and therefore, interworking between the optical layer and higher layers (such as SDH) is necessary.
- The optical layer can be divided further into sublayers. At least, a distinction between a wavelength routing layer and a fibre routing layer is useful, because fibre switches can be introduced very soon due to their simplicity.

These additional layers result in additional degrees of freedom for routing traffic demands. Apart from the choice between routing in the optical layer or in the electrical layers, also the choice between switching of single wavelength channels or switching of fibres arises for the optical layer. This is motivated by the requirement for a coarser switching granularity in the lower network layers in future due to higher transmission capacities. The choice of a network operator between wavelength and fibre switching also depends on the availability and cost of using either dark fibres or WDM systems.

In the most practical case, a mixture of these techniques may provide the optimum solution. This however requires to perform a very complex planning and dimensioning task.

Consideration of Network Architecture

The objective function could be chosen according to the network architecture. This could result in a more detailed consideration of specific features of the chosen architecture and therefore lead to better planning results. Especially for photonic networks, specific architectures seem to be promising which make use of particular properties of the optical technology.

An example is a topology based on multiple rings which provide optical transparency inside a ring and regeneration between different rings. Such an architecture allows fast and simple protection strategies. Moreover, the problem of transparency length is relaxed due to the restricted ring lengths. Nevertheless, the topological design of the rings and the definition of interconnection points remains a complex optimisation problem.

As long as photonic networks are not fully digitised on a link-by-link basis, location planning for regenerators is another complex planning task also influencing the objective function. The discussions are still ongoing whether the simplification of signal quality handling resulting from digitisation of the network will weigh up the reduction of transparency. Since at the moment all signals in the transport networks tend to be digital, this reduction may play no longer a role in the future.

Survivability

Achieving high survivability is a basic requirement for all photonic networks due to the high traffic volumes carried in the optical layer. Many different schemes and approaches are proposed and discussed in literature to achieve high survivability either with suitable network architectures or appropriate network dimensioning [Wu_92]. For all approaches, additional resources (so-called *spare capacities*) are required compared to the minimum required to fulfil the traffic demands (so-called *working capacities*). This results in additional costs which are sometimes even higher than the working capacity cost. Therefore, a trade-off exists between level of survivability and related costs.

However, the required level of survivability for a photonic network strongly depends on the service type looked at. For some high quality services, extremely fast (and maybe even hitless) protection could be required whereas for other services some slow restoration scheme is sufficient. Although this distinction is today mostly made in higher network layers, we expect for the future also a mix of survivability requirements for transport paths in the optical layer. It might even be the case that for some services there *must not* be any protection or restoration at all in the optical layer due to interaction problems with higher layers (see for example the ongoing discussion for SDH over WDM [Bone_98]).

There exist several methods (which can also be applied in combination) to take these survivability requirements into account during network planning:

- A strategy for the network design process can be defined (for example: applying 1+1 protection for all links).
- The financial cost of spare elements can be considered within the objective function.
- A measure for all non-protected or/and not-restorable traffic can be defined to evaluate the level of survivability.

Furthermore, it is interesting to note that WDM ring networks gain increasing importance also from a survivability point of view. Reasons are that the required network elements for rings are rather simple and that protection and restoration schemes can be implemented easily (see for example several papers in [OFC_98]). This corresponds to developments seen in SDH/SONET networks and may also have an influence on the considerations made for network architectures.

Scalability and Flexibility

These two aspects, which we summarise to “future proof”, gain increasing importance for network operators but are very difficult to evaluate quantitatively. Various aspects have to be considered as for example

- scalability of a network in terms of number of nodes,
- scalability of a network in terms of traffic volume,
- network flexibility to adapt to changed traffic patterns,
- scalability of network elements (size of nodes, number of WDM channels on a fibre, ...), or
- possibility to enhance the functionality (adding wavelength converters, ...).

The consideration of these aspects may take place

- by making *pre-planning* assumptions (for example scaling of traffic demands),

- by defining terms for the objective function or by using specific design strategies *during* the planning process, or
- by performing *post-planning* evaluations.

Simple examples of future proof measures are the percentage of unused network resources or the uniformity of the distribution of spare resources in the network.

However, a big difficulty is that traffic demand estimations for future photonic networks provide a big uncertainty. Moreover, traffic will not grow uniformly but with large geographic differences. Therefore a more sophisticated approach could be similar to the following which was applied for some case studies reported at OFC '98 [Card_98]. The planning process is performed for multiple consecutive 2-year periods with certain assumptions for the expected traffic increase. However, the resulting network is then loaded with a *randomly differing* traffic pattern to take into account demand prediction uncertainty. Then, a new prediction is done based on this traffic pattern and planning is performed for the next 2-year period. In this example, the case study was performed to show the advantages of WDM technology compared to other high-speed transport techniques. However, similar methods might also be applied for evaluating the future proof feature of several WDM network concepts.

5 Summary and Results

The great variety of aspects described in the previous sections indicates that considering all parameters simultaneously will lead to a very high problem complexity. But not only the problem complexity may become untractable, but also the interpretation of results becomes difficult due to overlapping of various influences and effects. Therefore, it is often necessary to concentrate on one single parameter to evaluate its influence or to learn about trends dominated by this parameter. However, mutual dependencies of multiple aspects cannot be seen with this method and in many cases it is even difficult to predict which parameters are really independent of each other.

It has to be noted that the definition of an objective function strongly depends on the goal of the planning process:

- If a concrete problem has to be investigated, the objective function should be as realistic and detailed as possible.
- To gain insight into basic properties or relations between parameters (for example the influence of wavelength converters on network performance), the objective function should be as restricted or simplified as necessary to be able to evaluate the desired effect.

Most of the work done in research is more related to the second goal whereas the planning department of a network operator usually has to deal with the first task.

Moreover, there are several methods of considering a parameter or aspect within the planning process:

- A strategy for the network design process can be defined in such a way that the parameter is automatically considered in the right way (for example providing two disjoint links for each traffic demand leads to a 100% restorability for all single link failures).
- The parameter under consideration is expressed in a measure which is commonly used for all aspects. In this way the parameter can be treated as an element of the objective function. Depending on the weight of this element in comparison to the other objective function elements, and also depending on the chosen optimisation technique the planning process will then try to find the overall optimum solution.

- The parameter is considered by defining constraints for the planning process. These constraints can be considered either as hard constraints (a violation leads to a rejection of the proposed solution) or as “soft” constraints (a violation is “punished” by resulting for example in higher costs).

Which of these methods should be applied depends on various conditions like availability of quantitative measures, optimisation technique, relevance of the considered parameter for the problem, ...

In the following, we pick out a few aspects (based on previously performed work) and summarise shortly some results.

Multi-Layer Planning

Photonic networks will first of all introduce an additional layer into today's networks (although in the long-term a simplification of the resulting multi-layer architecture could be imagined). Network planning therefore has to consider an additional layer which increases the complexity. Many approaches reported in literature therefore concentrate on one layer and take the traffic matrix resulting from the higher layer (e.g. the electrical layer) as an input for the lower layer (e.g. the WDM layer), for example in [Caen_97]. However, it is to expect that such an approach may not lead to an overall and global optimum solution.

On the other hand, all approaches which try an integrated consideration show the huge complexity of the problem (see for example [Pary_97, Spae_97]). Moreover, the qualitatively expected effect was confirmed that there exists a strong influence of the cost relations on the network solution. In an integrated multi-layer approach this may even lead to cases were one of the layers is not used at all [Spae_97].

Concerning multi-layer planning, we can therefore conclude so far, that we need either some simplifications to get the problem tractable, or a decomposition into smaller sub-problems has to be done (with the risk of achieving only sub-optimal solutions), or we have to restrict to relatively small problem sizes. Besides that, work for other more efficient solution approaches could be done.

Dynamic Traffic Conditions

Planning is usually performed under the assumption of static traffic conditions. However, during network operation dynamic changes of traffic flows occur due to random traffic variations, network failures, or changes in traffic patterns (for example during a day). Investigations show that a network planned for a certain traffic demand (called *static traffic demand*) will suffer blocking when this network has to carry dynamic traffic. This may even hold in the case when the mean offered load is significantly lower than the static traffic demand.

We show this effect at one example, although the concrete network performance (usually expressed by blocking probabilities) depends on many parameters such as network topology, network functionality (e.g., are converters available or not), traffic demand, characteristics of dynamic traffic, or routing strategies). Figure 4 shows results for a network without wavelength converters reported in more detail in [Spae_98]. The network is dimensioned for a certain static traffic demand using a simple optimised network planning based on shortest paths for routing the traffic demands. Then, this network is loaded with a dynamic traffic with a mean value ranging from 60 to 100% of the static traffic demand. Different routing strategies which consider a different number of alternative paths are compared for routing the randomly occurring traffic demands in the network. Some strategies well-known from classical networks are compared: *Fixed Source Routing* accepts only the shortest path used for planning, *Originating Office Control* allows only the originating node to select between multiple alternatives, *Sequential Office Control (SOC)* allows such a selection in all nodes, but only for *SOC with crankback* this control can be given back to a predecessor node in case a node finds no path for the next hop. Without going into the details, we see the effect described above: a dynamic traffic with the same mean value as the static traffic demand leads to very high blocking rates nearly independent of the routing strategy.

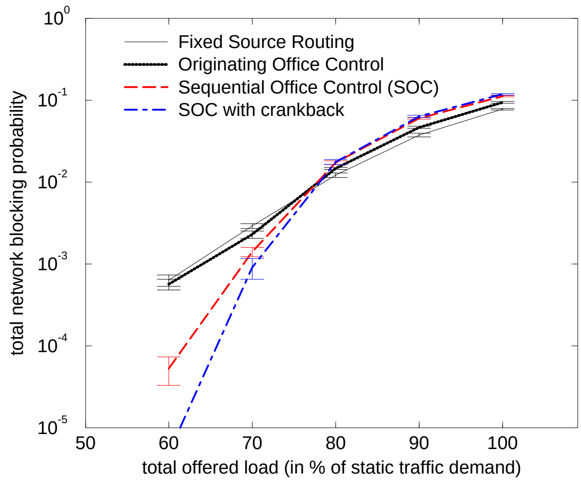

Figure 4: Comparison of routing methods in a WDM network without converters [Spae_98]

In this context, many questions are still open, such as the influence of routing strategies, or of traffic characteristics, or of the availability of wavelength converters on the network performance. Moreover, it is still not clear at all how future traffic in a WDM network will look like and to what extent dynamic behaviour will be seen at all.

6 Open Points and Directions of Further Work

A very basic open question is how useful optimisation is in general for network planning due to the facts that first, it is nearly impossible to consider *all* parameters which might have an influence and second, there are many uncertainties for the input parameters so that most network operators usually use more or less overdimensioning. However, optimisation is to our opinion useful for at least two reasons:

- To be able to evaluate different basic concepts, it is often necessary (and at least helpful) to compare the optimum solution achievable with the different concepts.
- Even if optimisation leads only to small improvements expressed in percentages, this may nevertheless be a significant financial amount due to the high element costs.

It is a difficult task to define quantitative measures for the different aspects mentioned in the previous sections. Further work is required to evaluate their importance. However, this will be an ongoing work since there is a permanent change concerning the relations between different aspects. For example, in the past transmission costs were dominating (or at least a significant part of) the overall network costs and therefore, network design and planning aimed at an efficient use of transmission systems. Today, however, we see rapidly decreasing costs for transmitting a bit from A to B and the costs for the equipment required in the network nodes becomes more and more important. This could also lead to a change in design and optimisation processes.

Finally, it is also not clear to what extent a combined consideration of various aspects gives advantages compared to a separate investigation of each parameter. On one hand, it is desirable to obtain comprehensive approaches which consider as many facets of the problem as possible, on the other hand this is limited by the complexity of the arising problems. Further work on efficient modular approaches is required.

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