Design and Operation of Survivable WDM Transport Networks

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Abstract

This contribution gives a short introduction in optical WDM (Wavelength Division Multiplexing) networks with special focus on wide-area transport networks and on a possible evolution scenario towards all-optical networks. Furthermore, design and planning aspects for a WDM network are discussed. This comprises a short overview on a planning process in general and a presentation of some specific facets of photonic networks such as the subject of wavelength conversion or survivability requirements. Finally, some aspects concerning the operation of WDM networks will be discussed.

1. Introduction

At the moment, bandwidth demands for telecommunication networks are rapidly increasing world wide. Reasons are an increasing number of users in communication networks and the development of new services with higher bandwidth requirements leading to an exploding growth especially of data traffic. Photonic networks represent a promising way to cope with these demands. Already today, optical point-to-point *links* are used in many networks and real optical *networks* are already becoming apparent.

Therefore, many urgent questions and problems are now arising including for example the design and planning of such networks, performance and cost evaluation, development of operation and management concepts, or the development of standards. This paper gives an overview of several of these points and related topics. Section 2 contains an introduction to photonic networks. This includes an explanation of the WDM technique and a possible network evolution scenario from today's networks towards optical networks. Section 3 deals with design and planning aspects, whereas Section 4 presents some operational aspects.

2. Photonic Networks

Based on the huge transmission rates achievable on fibres and due to the increasing "capabilities" of optical switching technologies, photonic networks provide a suitable basis to build real broadband networks to be used as high speed backbone networks [7, 17]. This section first describes Wavelength Division Multiplexing (WDM) as a key technique to exploit the fibre bandwidth. Then, application areas for photonic networks as well as a possible network evolution scenario are described. A possible future transport network architecture is presented which enhances today's transport networks by an optical layer. Finally, some components and systems required for building such networks are shortly listed.

2.1 Wavelength Division Multiplexing (WDM)

Most long-haul transmission links in telecommunication networks today apply already optical transmission over fibres using a single wavelength channel working at a specific bitrate, e.g. 2.5 Gbit/s carrying SDH/SONET (Synchronous Digital Hierarchy/Synchronous Optical

Network) signals. Due to increasing bandwidth demand, many network operators have to enlarge their link capacities which can be done in different ways. A straightforward solution is to install more fibres along a link. Roughly, this results in a linear increase of required equipment and therefore cost. Another approach is to increase the bitrate on the available channel by using faster TDM (Time Division Multiplexing) techniques (Fig. 1b). However, costs for electronic equipment are rapidly increasing with higher bitrates approaching the electronic limits. Moreover, there is a strong limit for maximum bitrates achievable over existing fibres due to fibre impairments.

Another very promising approach to increase link capacities is WDM (Fig. 1a). With WDM, multiple wavelength channels (i.e. frequencies) are carried over a single fibre, basically without any interference. This offers various advantages:

- Each wavelength can operate at a relatively low bitrate (e.g. 2.5 Gbit/s) thus requiring only “slow” electronics.
- There are multichannel amplifiers available which allow a simultaneous amplification of multiple wavelength channels (Fig. 1a). This leads to a drastic reduction of amplification cost for a network.
- Due to the lower bitrates per wavelength, also longer transmission distances can be achieved because several disturbing effects on fibres such as dispersion increase strongly with higher bitrates.
- System scalability is simplified due to the possibility of adding additional wavelengths without the necessity of changing the existing equipment.
- The transmission format on the wavelengths can be chosen independently thus allowing “transparent” channels which can carry for example arbitrary bitrates or signal formats.
- WDM provides the possibility of *optical by-passing*, i.e., traffic passes a transit node in the optical domain without requiring electronic switching equipment. Since in most networks a large part of the traffic at a node is transit traffic that need not to be handled at that node, switching costs can be reduced significantly.

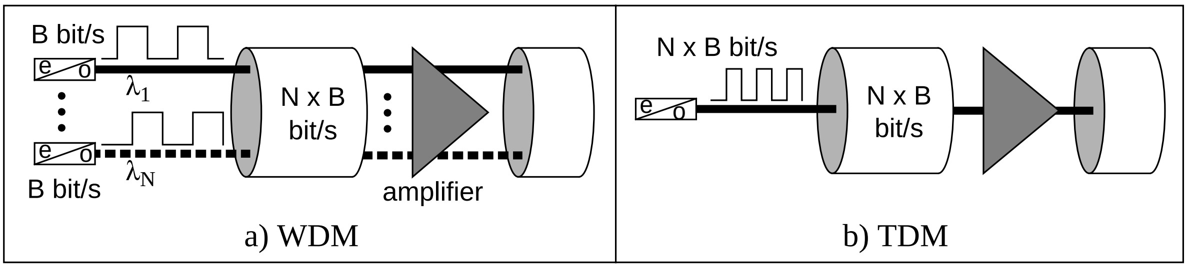

Figure 1: Schemes for a) wavelength and b) time division multiplexing techniques

Due to the listed advantages, WDM is a very successful technique at the moment and since first systems were introduced in 1994/95, the installation base is rapidly increasing. Usually, WDM will be combined with state-of-the-art TDM techniques for each channel. For example, in many cases it will be cheaper for an operator to install 4x2.5 Gbit/s than 1x10 Gbit/s SDH equipment. At the moment, systems offering up to 40 channels (with wavelengths around 1550 nm) each working at 2.5 Gbit/s are already commercially available, allowing 100 Gbit/s transmission over a single fibre. Systems with up to 400 Gbit/s are announced for this year, whereas in laboratory experiments already several Tbit/s were achieved [5].

2.2 Network Evolution Scenario

Application fields for photonic networks cover a broad range (Fig. 2). In the introductory phase, a usage in wide area networks is expected due to the high bitrates required there. But with decreasing system cost on the one hand and further increasing bandwidth demands on the other hand, photonic technology will be increasingly used in shorter distance networks like MANs (Metropolitan Area Networks) or LANs (Local Area Networks). Moreover, optical technologies offer certain advantages also for access networks. Of special interest are the so-called PON (Passive Optical Network) concepts due to their passive nature which allows cheap and reliable networks [11, 22].

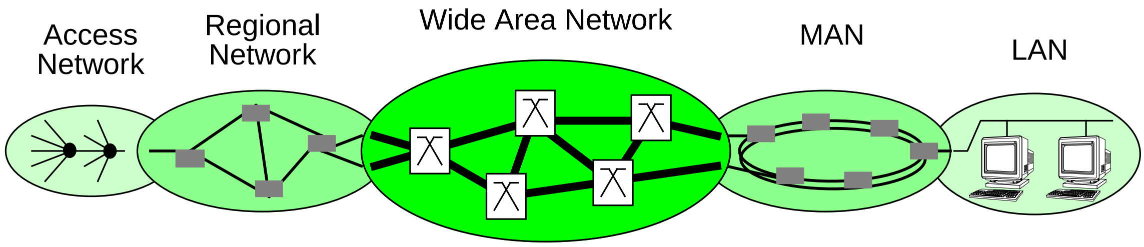

Figure 2: Application fields for photonic networks

Now, the question arises how networks can evolve from today's electrical to future optical networks. Fig. 3 depicts a possible evolution scenario with special focus on transport networks. This scenario represents a broad consensus in literature [14]. Today, point-to-point transmission with a single wavelength channel per fibre is more and more replaced by WDM point-to-point transmission. The next step will be to build optical rings with simple Add/Drop Multiplexers (ADMs) which can add and drop single wavelength channels (see also Section 2.3). A first generation of fixed ADMs is already available or announced by several system providers. The functionality of these rings can be enhanced by replacing fixed ADMs with tunable (i.e. configurable) ones.

Even more flexibility can be achieved by using Cross-Connects (CCs) which allow routing of wavelength channels from various inputs to an arbitrary output (see also Section 2.3). This leads to multi-layer networks in which electrical CCs (ECCs) known from today's networks (e.g. ATM or SDH CCs) and optical CCs (OCCs) will be used together. At the moment, many research projects are investigating OCC concepts and commercial products are expected in the next decade. In the long term, there might also be some kind of optical packet switching or optical TDM techniques available. However, today's research results show that these technologies still have to be improved a lot to achieve efficient solutions.

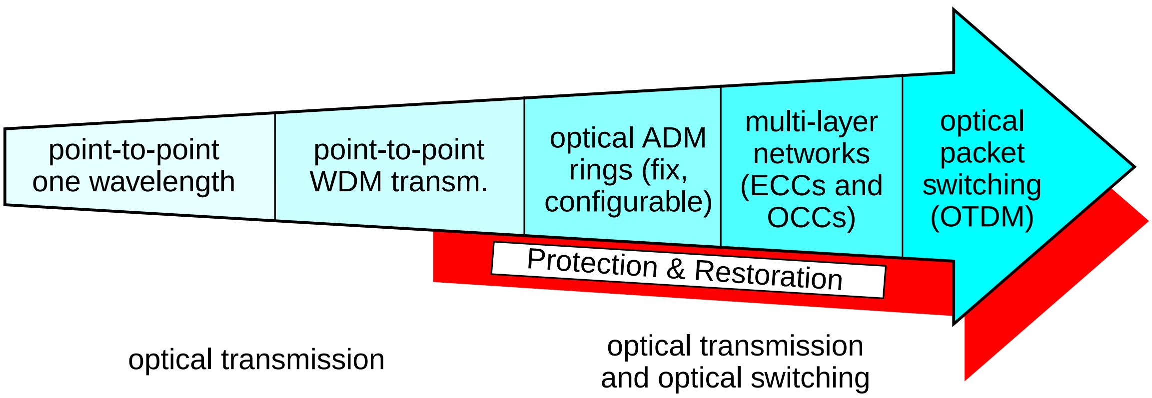

Figure 3: Network evolution scenario

Fig. 3 also indicates that the introduction of photonic technologies has to be accompanied by powerful protection and restoration mechanisms. They are necessary because the bitrates and therefore the amount of information handled by single network elements increase drastically and network operators have to guarantee a high survivability of their networks. Survivability aspects are described in Section 3.3.

2.3 Transport Network Architecture

Based on the evolution scenario described above, for the near future a transport network architecture as shown in Fig. 4 seems to be realistic:

- The existing electrical layer (e.g. SDH and/or ATM) is enhanced with an optical WDM layer.
- Ring topologies based on ADMs may be applied in the access and regional area.
- Meshed structures using CCs serve as long distance backbone networks.

Generic architectures for the nodes are also indicated in the figure. An OCC consists of a demultiplexing stage to separate the wavelength channels, followed by a space switch. Then, a wavelength conversion stage may follow before multiplexing the channels onto the outgoing fibres. For this generic scheme many different realisations are possible [1, 15]. ADMs are more simple consisting of only one input and one output. The fixed version indicated in the figure allows dropping and adding of two fixed channels, whereas configurable ADMs allow a selection which channels should be dropped/added.

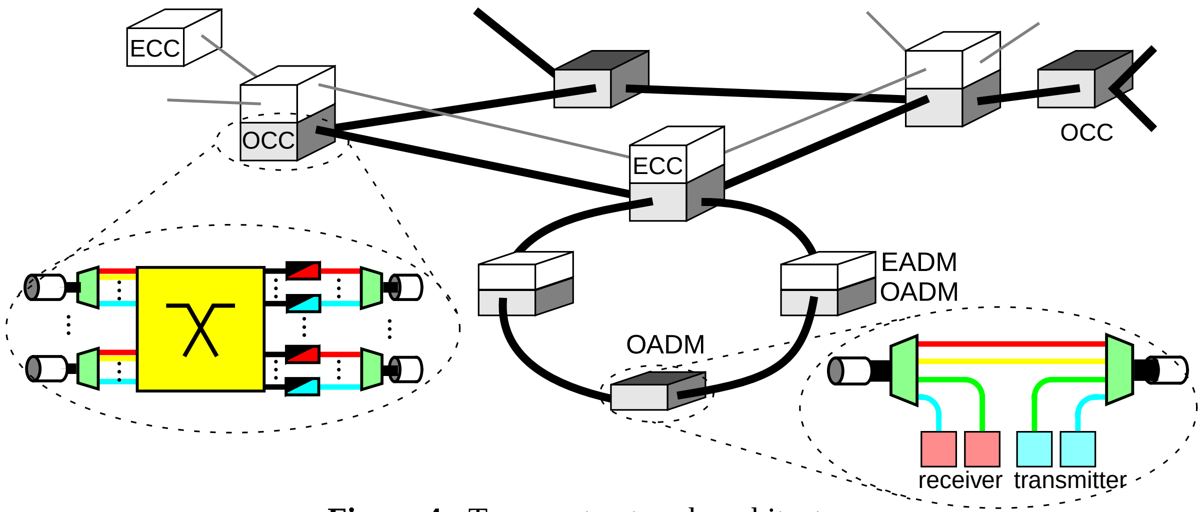

Figure 4: Transport network architecture

2.4 Components and Systems

Various components and sub-systems are necessary to realise photonic networks. Since this is also a very broad field, we will only list very shortly some basic components and refer to the literature for more details (good overviews can be found for example in [3, 13, 17]).

Transmitter
Usually, lasers are used instead of LEDs (Light Emitting Diodes) since they allow a higher power level and a smaller transmission spectrum. Lasers can be realised either as semiconductor or as fibre lasers.

Receiver
The basic element of a receiver is a photodetector (PIN or avalanche photodiode). In addition, amplifying elements and a decision circuit may be included.

Multiplexer/Demultiplexer
These components serve to separate (combine) multiple wavelength channels from (to) a single WDM signal. Usually, gratings are used as basic elements.

Filter
Filters are similar to demultiplexers. They allow isolating a single wavelength. For tunable filters, tuning speed and tuning range are important parameters.

Amplifier

Key elements for long distance networks are amplifiers. There are semiconductor optical amplifiers (SOAs) or fibre amplifiers available. For the latter, EDFAs (Erbium Doped Fibre Amplifiers) are the most famous example. They allow simultaneous amplification of multiple wavelength channels over a spectrum of approximately 30 nm in the 1550 nm range. This range is used for long-distance transmissions due to minimum attenuation of standard fibres.

Regenerator

In addition to amplification, a regenerator has to provide also reshaping and retiming of the signal. These elements are very important in digital networks, since they allow to reproduce a well-defined signal everywhere in the network. However, all-optical realisation of regenerating functions is very difficult. Therefore, electro-optical solutions (with the drawback of reduced transparency) have to be applied in the near future.

Wavelength Converter

Converter are required for wavelength interchanging operations in WDM network nodes. Many different realisations including all-optical as well as electro-optical approaches are under study at the time [21]. Since all solutions are still very expensive and difficult, many network concepts were developed which need less or no converters (see also Section 3.2).

Wavelength Switches

For large, fast, and scalable optical switches, there are also still many technological problems such as high signal attenuation. For slower switches, which are sufficient for switching transport paths, several solutions exist (e.g. mechanical switching). This holds also for very fast, but rather small switches as required for protection switching. For optical packet switching, research has begun but many improvements are still required to achieve solutions competitive to electrical packet switching techniques.

3. Design and Planning Aspects for Photonic Networks

A planning process comprises many tasks which can be assigned to different phases of an overall planning process for example as shown in Fig. 5. Usually, various decisions have to be made at the beginning of the design phase to reduce the problem complexity. Examples for decisions in this phase are what type of network should be planned (e.g. access or transport network), the decision for a certain network architecture and technology (e.g. WDM based transport network or pure SDH network), or whether “green field” planning or planning with consideration of existing infrastructure has to be done.

Based on these decisions, the next phase comprises mainly constructive tasks. Their goal is to design a valid network solution which fulfils all requirements in the most efficient way. Examples for tasks in this phase are calculation of traffic demands between node pairs, the topological design (where to place network elements), dimensioning of network elements (i.e. nodes and links), routing of traffic demands in the network (which may include wavelength assignment in case of WDM networks), or optimization steps. Many of these tasks are very complex and require high computational efforts.

Although already in this phase certain evaluations have to be done, usually a separate evaluation phase is required in which more detailed performance and cost evaluations are performed. An example is the investigation of the network behaviour under dynamic traffic conditions. Usually, this is done by discrete event simulations which are too time consuming to be integrated into the planning phase. Depending on the results of this phase, iterations of the decision and planning process may be necessary.

In the following subsections, some aspects with special interest for photonic networks are discussed in more detail.

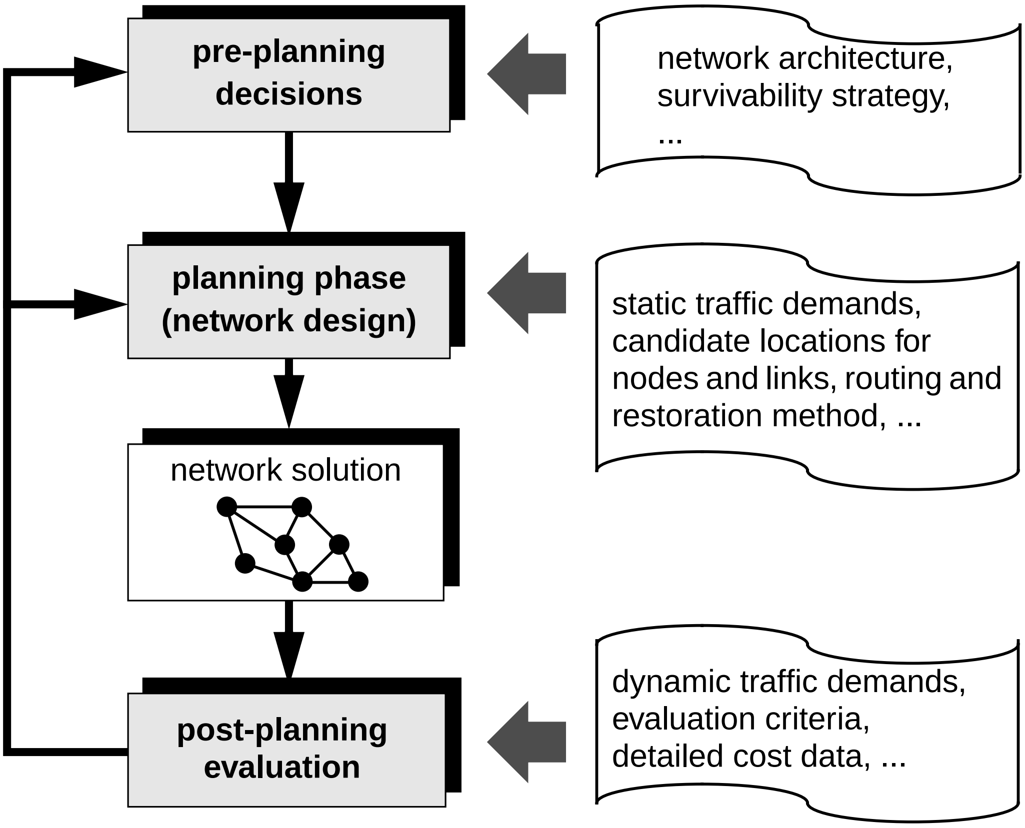

Figure 5: Main phases of a planning process

3.1 Optimization Methods and Objective Function

The central goal of a planning process is not only to find *any* solution which fulfils all requirements, but to find an *optimum* one according to certain criteria. Many of the resulting optimization problems are very complex so that no deterministic approach is known to find an optimum solution within reasonable time (many sub-problems are already NP-hard, see [6, 10]). Since photonic networks will add an additional layer to the existing networks, multi-layer planning problems arise which lead to further increasing complexity [19, 23]. Therefore, optimization techniques play an important role. Since many problems are of non-linear type, especially the so-called *non-deterministic search techniques* are widely used for planning tasks. These techniques comprise for example simulated annealing or evolutionary methods (genetic algorithms, evolutionary algorithms, ...).

A central element of optimization methods is the *objective function* (also called cost or optimization function). It allows the quantitative comparison of different alternatives according to certain criteria defined by the elements of the function. These elements may represent costs of physical network elements (e.g. transmission or switching systems), network performance aspects (e.g. blocking, delay, survivability measures, or flexibility and scalability), or operational and management costs [20]. Moreover, in some cases even constraints for the planning process can be included into the objective function.

3.2 Wavelength Conversion

In WDM networks, wavelength conversion leads to higher network flexibility by providing wavelength interchange functionality in switching nodes. However, wavelength conversion requires rather complicated and expensive technologies and the benefits for photonic networks are still under discussion. Therefore, many partial conversion concepts were developed. The wavelength conversion subject can be investigated at three different levels [20]:

On the *component level*, an isolated consideration of wavelength converter elements is done focusing on realisation techniques. On the *node level*, the influence on the node architecture and performance is investigated whereas on the *network level* the focus is on networking viewpoints. Some aspects are listed in Fig. 6.

component level	• different realisation techniques [21]: all-optical / electro-optical • influence in two respects: - cost (due to realisation efforts) - functionality (e.g. transparency or conversion range limitations)
node level	• various degrees of limited conversion • parameters for limited conversion: - *number* of converters in a node - *reachability* of converters (connectivity, pools) - *conversion range* (conversion spectrum) • influence on node architecture & equipment (e.g. no. of amplifiers)
network level	• influence on functionality (e.g. for routing or wavelength assignment), network architecture, topology, dimensioning, and costs • limited conversion aspects similar to node level - additional parameter: number of nodes with conversion (e.g. all nodes, only network interconnection nodes, ...)

Figure 6: Aspects of wavelength conversion in photonic networks

3.3 Network Survivability

Due to the high traffic streams carried in an optical layer, network operators have to guarantee a high survivability of such networks. Many different schemes are reported in literature [24]. Basically, *protection* and *restoration* schemes can be distinguished:

- *Protection* schemes are based on pre-planned spare capacities which are assigned to certain network resources “in advance”.
- *Restoration* schemes try to restore affected traffic after a failure by rerouting. All resources available at that moment are used. Therefore, these schemes are usually more efficient (i.e., they need less network resources) but slower than protection schemes.

Appropriate protocols for protection or restoration are required including mechanisms for fast error recognition. In WDM networks, protection and restoration mechanisms can work on a fibre level or on a wavelength channel level. Moreover, they can either work on a link-by-link basis (line restoration) or on paths (i.e. end-to-end).

Survivability schemes influence the planning process because in addition to the working capacities also spare capacities have to be provided. To integrate survivability aspects into a planning process, different strategies are available:

- In the “two-step approach”, the network is first planned without any spare capacities. They are added in a separate step. Although this is a practical method, usually only sub-optimal solutions are found.

- Integrated approaches try to dimension working and spare capacities in a single step (see for example [16]). This method provides chances to find better network solutions, suffers however from higher complexity.
- The “level of survivability” is expressed as an objective function element and thus included into the optimization process. However, in many cases it is difficult to find an appropriate quantitative measure.
- “Design rules” are applied during planning leading to certain properties of the network which guarantee the desired survivability (e.g. using a ring topology).

It should be noted, that different service types may require different levels of survivability in the network. Although this distinction is up to now mostly made in higher network layers, it can be expected that in future there will also be different survivability requirements for optical transport paths requiring higher flexibility in the optical layer.

4. Operational Aspects for WDM Transport Networks

At the moment, many network operators are introducing WDM point-to-point links. For the operation of these links mainly physical layer problems such as dispersion compensation, power management, monitoring of physical parameters, or fault recognition and restoration are arising. Up to now, each WDM system is built by a single system provider which also provides a proprietary OAM (Operation, Administration and Maintenance) framework. So far, no interworking between systems of different WDM providers is guaranteed. Moreover, from a traffic point of view, these systems serve as static transport paths for which no (re-)configuration possibility is required.

When going from point-to-point links to networks, the physical layer problems will become even more complicated due to parameter variations occurring during network operation. Many of these variations cannot be foreseen. For example, the attenuation or dispersion of an optical path strongly depends on the path length and the network elements the path crosses. However, these factors depend on the routing for the path and therefore they cannot be known in advance (i.e. during network installation). One way to solve these physical layer problems is defining worst case limits. However, this leads very often to stringent component requirements and network limitations.

Fault recognition is also more complicated for networks compared to point-to-point links [2]. This is especially true for determining the location of faults. For example, a disturbing noise source in the network may lead to threshold violations various segments “down the stream” due to amplifiers along the line which also amplify the noise signal. Many problems of this type are still not solved.

Moreover, interworking is becoming a difficult topic. This includes interworking between multiple optical (sub-)networks, which may even belong to multiple operators. Furthermore, for the interfaces to and the interworking with existing electrical layers (especially SDH) still no really satisfying solutions are known. One big problem is the fault management in multi-layer networks: it is important to define which layer has to react on a certain network fault [8]. A fibre break for example would interrupt several wavelength channels which may carry hundreds of SDH transport paths each carrying thousands of phone calls or data connections. This would result in “alarm flooding” (see Fig. 7). Thus, it is obviously very efficient to react on fibre breaks directly in the optical layer instead of restoring hundreds of thousands of end-user connections. On the other hand, an error concerning only one end-to-end connection would be handled more appropriately in higher layers.

A problem is however that higher layers may already start to react on fault conditions before lower layers have finished their protection or restoration activity. An SDH network for example recognises fibre breaks already after 2.3 μs which is too fast for any optical layer to complete restoration activities [17]. Therefore, additional interworking standards are required. At the moment, a feasible solution for the mentioned problem consists in introducing so-called “hold-off” timers for higher network layers to delay restoration activities.

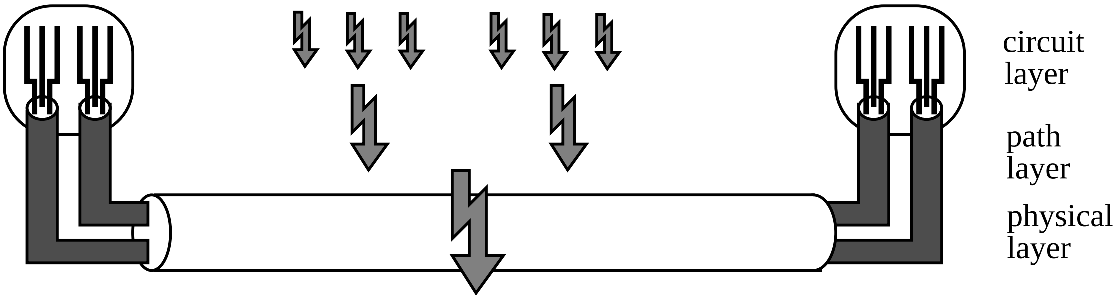

Figure 7: Alarm message flooding in higher network layers

In networks, handling of dynamic traffic conditions is an important task. This comprises routing for arising connection requests and an appropriate resource management. Dynamic routing in photonic networks is an arising research topic with some new aspects in addition to classical routing problems. Examples are an efficient use of wavelength converters or the consideration of physical parameters for the routing decision [18].

Finally, the interconnection with the network management system is a key issue. For optical networks too, the basic management functions (configuration, performance, fault, security and accounting management) have to be fulfilled. So far, work on related topics has just started. This comprises for example the definition of appropriate management information bases (MIBs) or the interfaces to the TMN (Telecommunication Management Network) [4, 12].

5. Conclusions

This paper gave an overview on photonic networks based on WDM as a key technology to efficiently use the huge bandwidth available on fibres. A realistic scenario for a future transport network architecture which uses cross-connects and add/drop multiplexers was described. Various aspects concerning the design and planning for photonic networks were discussed showing that many problems still have to be solved to achieve efficient network solutions. Moreover, it was shown that many questions are still open concerning the operation and management of optical networks. Apart from solving these problems, the results and knowledge from research and development work done so far [9] must now also lead to the development of standards. This work has already started at ITU-T (International Telecommunication Union - Telecommunications Sector) and first drafts covering physical as well as networking aspects are either available or announced. But further progress is needed to provide the way for a successful introduction of photonic networks. Due to the large transport capacities, these networks are an essential part of the telecommunications infrastructure required for the future information society.

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