Design and Planning Aspects of Future Photonic Transport Networks

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Summary: Photonic transport networks are expected to meet the increasing bandwidth demand in telecommunication networks which will arise with future broadband services and applications. In this paper, we will discuss various requirements which have to be considered by network planning. This comprises technology and infrastructure constraints, traffic requirements, and migration paths from the electrical to future optical transport networks. Moreover, different strategies for network planning are outlined. In particular, strategies for resource distribution and for routing in photonic transport networks are presented.

1 The Future Transport Network

Future services and applications will increase bandwidth demand in telecommunication networks. Today, optical technology is already used providing for high link capacities. However, these capacities can be increased significantly by employing WDM (Wavelength Division Multiplexing) in multichannel systems. Additionally, future photonic transport networks will be able to switch very high bitrates by applying flexible and efficient cross-connecting in the optical domain combined with wavelength conversion to further improve network performance.

As such 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, Quality of Service parameters and constraints given by WDM technology or network infrastructure. The objective is to achieve maximum use of wavelength capacities and node resources.

1.1 Architecture

Since future networks have to be evolved from existing ones, two layers are proposed: optical connections based on WDM and electrically terminated connections (figure 1).

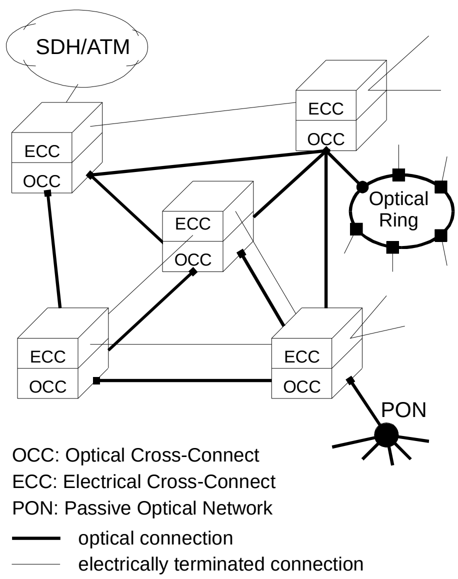

Figure 1: Photonic Network Architecture

In each of these two layers paths or virtual paths may be provided [13,14]. Cross-connecting functions will be performed by optical and electrical Cross-Connects (OCC / ECC). OCCs will realise switched connections (optical channels) whereas in the electrical domain well-known techniques such as SDH (Synchronous Digital Hierarchy) and ATM (Asynchronous Transfer Mode) are expected to further dominate.

Apart from using photonic technology in wide-area networks, an effective use can be foreseen with dedicated architectures for special areas as for example ring networks used as very fast backbones. There, optical add-drop multiplexers (OADs) could be applied instead of complex CCs [8]. PONs (Passive Optical Networks) suitable for distributive services or local access networks constitute another promising application of photonic technology [3,5].

1.2 Functionality

All-optical transport networks offer the possibility to realise transparent channels which are completely independent of the employed transmission signal format. Even analog channels may be provided. This feature will open up new application areas.

Today, just a fraction of the fibre bandwidth is used due to the fact that only a single wavelength is transported per fibre. A wide scope of new network functionalities arises by the use of WDM leading to large transmission bandwidths. Flexibility and reliability is increased by supporting multiple connections on a single fibre and hence providing additional protection and restoration facilities.

2 Planning Requirements

2.1 Technology Constraints

For the planning of photonic networks, technology constraints play an even more decisive role than for electrical network planning. This is due to the less mature technology causing network costs to rapidly increase if more complex architectures are realised.

Some of the constraints result from physical effects as for example propagation delay while others are caused by technological restrictions and may change rapidly as photonic research progresses [6,9].

Fibre technology has already reached a relatively stable state in which high performance fibres with sufficient loss and dispersion values are available. Moreover, some million fibre kilometres are already installed so that future network development will be founded on this basis.

Signal amplification and dispersion compensation are required to cope with long distance transmission. Whereas EDFAs (Erbium Doped Fibre Amplifiers) are still expensive but already usable, dispersion compensation is furthermore a research and development topic, in which promising results were reported recently [4]. Moreover, the maximum regenerator distance and the number of wavelengths simultaneously provided by WDM are important constraints for the planning process.

The design of photonic network nodes is another large research area. Yet unsolved questions concern node components as switching elements, multiplexers/demultiplexers, lasers, receivers, signal regenerators, wavelength converters or integrated opto-electronic components. However, for some components promising results have already been achieved.

2.2 Infrastructure

In most cases, future networks and in particular wide area transport networks cannot be started from scratch due to high investments. Accordingly, network planning has to consider the existing infrastructure in a twofold manner.

First, components already installed for photonic networks should be used as far as possible, even if they are sub-optimal from a technical point of view. One example are the installed standard single mode fibres which require polarisation-independent and therefore more costly switching devices compared to polarisation-preserving fibres [7]. It is necessary to evaluate whether replacing the fibres or implementing costly devices for the old fibres is more appropriate.

Second, migration from the existing electrical to an all-optical transport network must be possible by supplementing the existing electrical infrastructure step by step. In future, the ATM/SDH and the WDM network will be used in parallel.

Additionally, planning has to take into account further infrastructure constraints. This comprises ducts along which fibres can be laid as well as possible locations for network nodes. The latter may get a quite important issue due to the increasing security requirements arising with the high bitrates transported in photonic networks.

2.3 Traffic

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. It is supposed that the traffic load in the future photonic transport network differs significantly from the load in present networks out of two reasons: (1) new services will increase bandwidth demand for single connections; (2) progress in technology allows the concentration of many connections into one optical path of the transport network. Therefore, the traffic characteristics of a single connection (e.g. burstiness) are not important.

To get realistic estimations for the traffic requirements of the future network, it is necessary to improve the knowledge of traffic behaviour. Obviously, measurements in comparable transport networks would be convenient, but they are hardly possible due to lacking network and service implementations. Up to the availability of appropriate testbeds, the only practicable way to get traffic parameters is therefore to do partly measurements in present networks and derive parameter estimations.

But even if the traffic requirements are known, another problem remains as in general they are given as bitrates. In a photonic network these bit streams can be multiplexed into a single transport stream in various ways either in the time domain or in the frequency domain. Time division multiplexing (TDM) will be realised merely in the electrical domain for the reason that optical TDM will most likely not become a mature application in the near future. Frequency multiplexing however will be done in the optical domain by using WDM techniques.

2.4 Migration from the existing Electrical to the Optical Network

The ATM/SDH network and the WDM transport network will coexist in the foreseeable future. The latter will be realised in several steps. Initially, cross-connecting by means of SDM (Space Division Multiplexing) as well as multiplexing and demultiplexing will be realised optically in the nodes, whereas wavelength conversion and signal regeneration will be performed electrically. In the long-term, these functions may also be realised optically.

A TMN (Telecommunications Management Network) will control both, the WDM transport network and the ATM/SDH network. It is expected that the electrical network will be used for TMN due to the mature technology. Operation and Maintenance (OAM) however may be done in the optical network for example by applying a separate wavelength in the fibres.

3 Planning Strategies

Photonic networks based on WDM contain various scarce resources as for example fibres, wavelength converters or regenerators. Therefore, planning strategies are required for dimensioning the fibre network and the nodes with their resources. Furthermore, it is necessary to route connections through the optical network and to assign wavelengths to the connections. The mutual dependencies between dimensioning and routing add yet another degree of complexity to the planning process.

3.1 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 and in the near future, their functionality will be performed in the electrical domain. Economical all-optical realisations may get possible in the long term.

An important feature is that these resource elements can be located at various places (i.e. 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.

A straightforward method for network planning including the arrangement of resources can be divided into two steps: (1) The network is optimised without considering the arrangement of resources but other criteria such as for example costs. (2) For each connection the required resources (e.g. wavelength converters, regenerators) are provided conforming to the network topology derived from step (1). Step (2) is quite simple to realise since no additional effort is made. However, solutions according to this method may have some drawbacks. If for example the traffic requirements change, some wavelength converters may be unused whereas new converters may be needed at other locations.

To overcome this problem, a more intelligent planning process can be applied which includes an optimisation of resource distribution according to various criteria. For example, nodes can be equipped with resource elements corresponding to their size. This considers that on average bigger nodes will require more resource elements than smaller ones. Additionally, it can be expected that wavelength converters will be required in particular in network nodes that have to cross-connect a lot of wavelength paths from different directions. Hence, these nodes should be preferred as locations for wavelength converters.

A considerable support for the realisation of these distribution strategies are pool concepts which allow a more efficient use of scarce elements [11]. Pools can be provided for network areas, for a node, or only for a part of a node. Consequently, the design of OCCs depends on the applied pool concept.

Figure 2 shows the generic architecture of an OCC containing a pool of resource elements. The light of the input fibres is demultiplexed to separate the wavelengths transported in WDM mode on the fibres. Each wavelength can be routed either directly to the output or to the pool. After passing the pool, in which for example a signal regeneration can be done, these wavelengths are also routed to the output. There, multiplexers combine the light for each outgoing fibre.

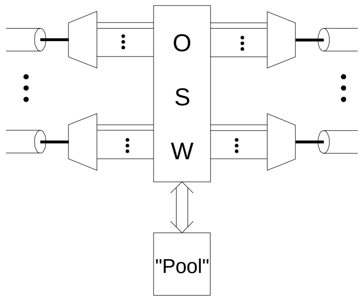

Figure 2: Generic architecture of an optical cross-connect with a pool of resource elements

Various architectures for pool concepts can be realised which differ in the number of required node elements (e.g. size of the optical switch) as well as in the efficiency of their use. For some pool concepts a performance evaluation was done considering in particular the relationship between blocking probabilities and the number of wavelength converters in a node [15]. It turned out that in general converters decrease blocking probabilities 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.

In photonic networks, other resources exist which do not offer a positioning flexibility or do not allow a shared use. Two examples are signal amplification and dispersion compensation, which have to be provided along transmission lines and cannot be shared between multiple fibres. However, appropriate routing strategies may lead to high fibre usage resulting in a reduction of fibres and amplifiers.

A severe problem is the rapidly increasing number of configurations which arise with intelligent distribution strategies. The large computation times required for finding the optimum solution may nevertheless be acceptable for planning new networks. Network costs can be decreased and flexibility against future changes can be significantly improved by appropriate distribution strategies.

3.2 Routing

The task of routing is to find a valid route from source to destination. In WDM networks, routing comprises additionally the task of assigning suitable wavelengths to the optical channels. First of all, it is therefore necessary to determine the number of optical channels needed for the given bitrate requirements.

In general, the bitrate of a single connection will not fill exactly the bandwidth of an optical channel. Various strategies for optical channel assignment are possible which can be divided into two categories: (1) assigning optical channels for each single connection and (2) grouping strategies which cover multiple connections.

As long as optical and electrical networks exist in parallel, the required optical channels for a single connection can be determined as follows. First, the connection bitrate can be fully covered by channel bandwidths, even if a channel is only partially used. Second, the use of an optical channel for a connection can depend on the degree of channel exploitation. That is, a bitrate threshold can be defined which must be exceeded by a connection to get a new channel assigned. This allows a more efficient use of channels and therefore wavelengths. On the other hand, the traffic below the threshold has to be transported in the electrical network.

More efficient strategies are possible if one optical channel is allowed to be used by multiple connections. The necessary multiplexing can be done by TDM in the electrical domain. Thus, traffic which uses a section of the network in common could be combined. This is quite simple to realise. After valid routes are found for all connections, it has to be checked which sections are commonly used by multiple connections. Then, this traffic is combined so that a maximum use of channels is achieved.

This strategy can be enhanced by additionally allowing some connections to be re-routed. Furthermore, a part of the traffic can be transported in the electrical network, so that a maximum of fully occupied channels can be achieved. The drawback of this method is the large number of combinations which have to be investigated. Whereas this problem is already very complex in small networks, for larger networks a restriction on some special cases seems to be inevitable.

For routing, physical constraints have to be taken into account as for example the condition that all wavelengths on a fibre must be different. Limits are also given by the maximum loss or dispersion of signals which determines the maximum amplifier or regenerator distance, respectively.

Two routing categories can be distinguished. One is static routing under fixed conditions performed as a part of the planning process. The other comprises dynamic routing under changing conditions such as a fibre break during network operation.

Static Routing

During network planning, more time can be spent for routing optimisations than during network operation. An appropriate routing strategy can optimise various parameters.

In principle, it is possible to minimise the length of all connections in the network (called *connection kilometres* in the following). This can be realised by choosing for each connection the shortest path being allowed by the ducts. The advantage of this strategy is, that the route for each connection is determined unambiguously and the following algorithm can be applied. (1) Choose the shortest path for each connection. (2) Provide the required capacities and resources. For step (1), numerous algorithms are known (see [1]).

Moreover, the number of nodes between a source and their destination can be minimised. Each node transit occupies resources and contributes to signal degradation due to imperfect node elements. Therefore, the more nodes are passed, the more costly signal regeneration has to be provided.

Apart from minimising the length of each connection, it may be advantageous to minimise the total length of used fibres in the network (called *fibre kilometres* in the following). In general, this will lead to longer connections but to fibres utilised with a higher percentage. A minimum of fibre kilometres can be achieved by a minimum spanning tree that fulfils all traffic requirements, i.e. the traffic flow through any link does not exceed the link capacity. In this case, the well known problem of finding a capacitated minimum spanning tree has to be solved [10].

Static routing also has to provide protection paths to ensure sufficient network integrity. However, if all connections are routed in such a way that an efficient use of fibres or node resources is achieved, the trade-off between network efficiency and integrity against failures has to be considered. For example, an efficient use of fibres under error-free network operation leads to reduced spare capacities (e.g. empty fibres or unused wavelengths). As a consequence, there are fewer possibilities to deal with fibre breaks or changing traffic conditions. Hence, resource distribution strategies are also affected since they have to provide an appropriate dimensioning of spare capacities.

Dynamic Routing

On the one hand, dynamic routing is necessary for a flexible assignment of resources due to changed traffic requirements arising for example with different configurations for day and night or leased line services. On the other hand, unforeseen failures can occur. Whereas single failures may have disastrous consequences already today, in future photonic networks this effect will be further increased due to the very high bitrates carried by each single component [12]. As a consequence, providing enough spare capacities and very fast restoration mechanisms becomes a decisive factor for network planning.

Two important groups are centralised and decentralised restoration mechanisms. Furthermore, pre-planning and adaptive mechanisms can be distinguished. Other well known techniques are link and path restoration. All these mechanisms can be combined with different traffic splitting strategies [2,16].

Due to the very fast reaction times needed in photonic networks, most of the yet known restoration mechanisms cannot be applied directly but have to be modified to meet the necessary requirements.

3.3 Parameter Interdependence

Resource distribution strategies and routing strategies are not independent of each other and both have to be considered by network planning.

One example is the dependence between the fibre kilometres and the number of converters. The qualitative relationship is shown in figure 3 whereas the exact shape depends strongly on the network topology. If no converters are employed, a certain number of fibres is required to route all connections without wavelength conflicts.

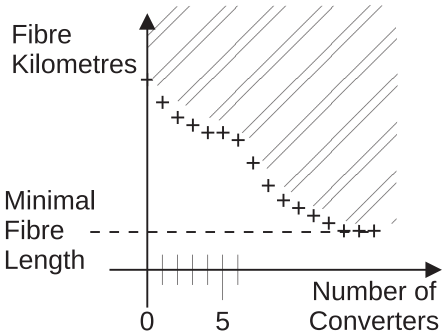

Figure 3: Qualitative relationship between fibre kilometres and number of converters

Increasing the number of converters allows more connections to use the same fibres as the number of wavelength conflicts can be reduced. Therefore, the required fibre kilometres decrease. However, there exists a certain limit at which additional converters lead to no further reduction of fibre kilometres. This limit is given by the minimal fibre length needed to connect all nodes. Obviously, there must be enough capacity for all connections in the network.

For any given number of converters, a certain minimum of fibres is required (depicted by '+' in figure 3). However, additional solutions with a higher number of fibre kilometres are also possible. This is depicted by the hatched area in figure 3, which indicates the possible region for the discrete solutions.

Another example is the relation between the fibre kilometres and the connection kilometres. A full mesh will lead to shortest path connections but to a high number of fibre kilometres. For real networks, infrastructure constraints have to be considered which in general will not allow a full mesh along the straight lines between the nodes. Compared to the necessary fibres for shortest path connections, the fibre kilometres can be reduced by allowing some connections to be routed on longer paths. Two limits can be observed. One is given by the minimum of connection kilometres which is achieved with shortest paths for all connections. The other limit denotes the minimum of fibre kilometres needed to connect all nodes.

For a successful network planning, tools which are able to handle the complex relationships between the various parameters are necessary. An essential part of such a tool is an appropriate cost function which considers all constraints and allows the weighting of different parameters. These parameters may comprise Quality of Service aspects or cost functions for various network elements as for example fibre kilometres, number of amplifiers, or number of ports at the nodes.

4 Conclusions

This paper presented various aspects which are expected to have significant influence on the design process of future photonic transport networks. In particular, strategies for resource distribution and for routing were discussed.

Additionally, some features of photonic transport networks were presented which force different constraints (e.g. technological constraints) in a planning model compared to electrical networks.

In some work areas, previous results can be adapted. For example, many routing strategies were already investigated in the past so that these results can be taken as a basis for future developments. For many other tasks, however, further basic investigations are necessary. In particular, models for both static and dynamic network behaviour are required. This comprises spare capacity planning or protection and restoration mechanisms.

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