WAVELENGTH ROUTING WITH GROOMING AND PROTECTION

Csaba Gáspár, Tibor Cinkler, Gábor Makács, János Tapolcai
High-Speed Networks Laboratory, Department of Telecommunications & Telematics
Budapest University of Technology & Economics, Budapest, Hungary
cinkler@ttt.bme.hu

Abstract

Whenever the traffic demands have bandwidth by orders of magnitude lower than the capacity of λ-links it is not worth assigning exclusive end-to-end λ-paths to these demands, i.e., sub-lambda granularity is required. Furthermore, the number of λs per fiber is limited and costly. To increase the throughput of a network with limited number of λs per fiber traffic grooming capability is required in certain nodes.

An efficient and general graph-theoretic model (the Wavelength-Graph (WG)) has been proposed that allows simultaneously (1) routing the λ-paths and assigning wavelengths to them; AND (2) routing the upper layer (e.g., IP) traffic and grooming it into the λ-path system.

The gain of traffic grooming is investigated as well as its impact onto shared path protection.

1. Introduction

Here we consider case of Wavelength Routing Dense Wavelength Division Multiplexing (WR-DWDM) Networks and one layer built over it. In the WR-DWDM layer a wavelength path (λ-path) connects two physically adjacent or distant nodes. These two physical nodes will seem adjacent for the upper layer built over it.

This upper layer is an "electrical" one, i.e., it can perform multiplexing different traffic streams into a single wavelength path (λ-path). Similarly it can demultiplex different traffic streams of a single λ-path. Furthermore, it can perform re-multiplexing as well: Some of the demands de-multiplexed will be again multiplexed into some other wavelength paths and handled together along it. This is often referred to as traffic grooming [1]. Further on we well refer to it as grooming. Electri-
cal layer is required for multiplexing packets coming from different ports (asynchronous time division multiplexing).

This upper electrical layer can be a classical or “new generation” SDH/SONET, MPLS, ATM, GbE, 10 GbE or based on any other technology. The only requirement is that it must be unique for all traffic streams that have to be de-multiplexed, and then multiplexed again, since we can not multiplex e.g. ATM cells with Ethernet frames directly.

More generally, we can consider this two-layer approach as two layers of a 4-5 layer GMPLS/ASTN network [2][3].

Many excellent papers deal with design, configuration and optimisation of WDM Networks. See, e.g., [4]-[10]. Some of these methods can be generalised for design of the proposed two-layer network as well.

Our objective is to configure the upper layer and the λ-path system optimally without separating these two network-layers. Although it improves the quality of results, the complexity of the problem grows.

As the result of optimisation we decrease the traffic to be processed and carried in the electrical domain over-bridging the speed limits of electronics. Since a considerable part of the load of electrical, e.g., SDH, ATM or MPLS switches is bypassed by the optical switches much larger networks with higher loads can be realised by the current technology, offering better granularity and using optimally any limited number of wavelengths (λs).

In Section 2 we present the model of the network with different node-types. In Section 3 the path-protection alternatives (dedicated vs. shared) are given for protection at the upper (electrical) layer. In Section 4 we formulate the problem and propose methods for solving it. Section 5 explains the applied methods and presents the numerical results while in Section 6 conclusion is drawn with comments on the proposed methods.

2. The Wavelength Graph (WG)

The objective was to provide a general model for configuration of WDM networks with different types of nodes and arbitrary topologies. Although the most widespread topology is ring or interconnected rings, the model must be able to handle any regular or mesh topology. The nodes can also be quite different: Optical Add-and-Drop Multiplexers (OADM), Optical Cross-Connects (OXC) with full or limited, optical or opto-electrical λ conversion or even an Opto-Electrical Cross Connect (OEXC). The protection strategies can also be quite different. All these aspects are taken into account in the proposed model. First the link model is described followed by models of different nodes. In this section
we assume that all traffic demands are bidirectional and symmetrical. In this case the network can be modeled by an undirected graph. The model can be simply generalised for un-symmetrical demands, by using directed graphs. In later case the model is more complex and for this reason the algorithms will run slower.

2.1 Model of Links

![Diagram of network model](image)

*Figure 1. Modeling edges.*

A network consists of nodes, and links connecting the nodes. This can be modeled by a graph: a node is a vertex and a link is an edge. Having multiple λs we will represent a λ of a link as an edge in the graph of wavelengths according to Figure 1 that shows the network proposed in [11]. To prioritise filling up λs one-by-one we can assign slightly different weights to different channels of one link. For example, edges representing λ1, λ2 and λ3 will have slightly different weights, e.g., 10.1, 10.2 and 10.3 respectively.

2.2 Model of Nodes

A node is modeled by a subgraph. The subgraph-nodes are the certain λs at the switch-ports, while the weighted edges represent the costs of transitions, terminations, conversions, etc. There are different types of nodes. Models of nodes differ for these. Here will be shown some examples. In similar manner a model can be derived for any additional node-type.
**Optical Add-and-Drop Multiplexer: OADM.** The OADM Nodes have in general two bi-directional ports (4 fibres). Their function is either to transmit a λ channel or to terminate it and usually they do not allow λ-conversion. These devices are capable to add or drop wavelength channels (typically one to four of them).

The weights assigned to edges representing termination (e.g., 50) are higher than weights of transition (e.g., 25), because transition is preferred to termination. According to the proposed model (Figure 2) the traffic streams can enter or exit the OADM crossing vertex E or can be even re-multiplexed, i.e., groomed.

After establishing any path through the switch weights have to be updated if any new λ-path was created. When a λ-path of a considered wavelength transits the OADM, the cost of the edge representing transition will be changed from 25 to 0, and the weight of both edges for termination will be changed from 50 to a very large value (e.g., infinity) or it will be disabled (e.g., temporarily deleted). Therefore, terminating that λ that had transition through that node will not be possible in that node anymore. For this reason algorithm will be sensitive to order of setting up λ-paths. When a λ-path is terminated the cost of transition edge will be very high (e.g., infinite) but weight for termination will still not be zero but somewhat smaller than the initial cost was. This principle will apply to all other node-models as well.

**Optical Cross-Connect with Electrical Core: OEXC.** In the model shown in Figure 3 each pair of nodes should be connected by an edge. All edges should have equal weights. Instead of connecting all pairs using n×n edges we use n edges and one node. This simplifies the model. Each incoming channel is converted to electrical domain switched by a
space-switch and again converted to the optical domain to arbitrary $\lambda$. Each termination, transition or $\lambda$ change of a $\lambda$-path has the same cost (e.g., 25). Therefore, all edges have the same weight (e.g., 25/2). An OXC performs space switching, and wavelength conversion, however, it does not support time division multiplexing, i.e., it does not support grooming. Therefore care must be taken, that if a pair of internal links within the node model has been used, no further branching is allowed along it within that node.

**Figure 3.** Model of OXC Nodes.

**Figure 4.** Model of a Simple Optical Cross-Connect Node (without $\lambda$ conversion)

**Optical Cross-Connect with All-Optical Core: OXC.** An Optical Cross-Connect has more than two ports, e.g., four bi-directional ports according to Figure 1. In an OXC a $\lambda$-path can make transition to any output port which supports that $\lambda$, and that $\lambda$ is not yet used. This OXC type (without $\lambda$ change capability) will be referred to as *simple* OXC (see Figure 4). In this case one incoming channel can exit at any
of the remaining output ports where that λ is supported and not yet used.

In some OXC devices λ translation (change, conversion, shifting) is also supported. This node will be called OXC. Its model is showed in Figure 5. For this node any incoming channel can exit at one of 11 remaining channels. Now there are 3 possibilities for λ-path transition since there are channels of the same wavelength on all ports in our example. For λ change there are 8 possibilities. It has higher cost (e.g., 2×50=100) than the λ transition. λ conversion is modeled by conducting the traffic stream through node E.

![Figure 5. Model of an Optical Cross-Connect Node (with λ conversion)](image)

In some cases the traffic stream termination is also among the functions of an OXC. In that case the model does not need any change. The only difference will be that there will be some traffic offered to that OXC node which can be modeled by offering traffic to node E and considering it as an end-node. In this case traffic-stream re-multiplexing (grooming) capability is also performed by node E.

**Modeling opto-electro-optical conversions, multiplexing and re-multiplexing.** If we want to differentiate the simple wavelength-conversion from the electrical signal re-multiplexing (grooming) a more complex model is needed. An example has been shown in Figure 6 for an OADM node for simplicity reasons, which can be extended to any other node-type. As can be seen node E has been substituted by a fully connected sub-graph. In this case assigning costs to internal edges the costs
of wavelength-conversion and signal re-multiplexing (grooming) can be differentiated.

All-Optical λ conversion is not supported by all OXCs. Therefore, the optical signal is terminated and passed to the electrical layer where space switching or space switching with time switching (re-multiplexing) is done and then the resulting electrical signal passed back to the optical layer.

![Diagram of OADM nodes and wavelength channels](image)

*Figure 6.* Modeling opto-electro-optical conversions and re-multiplexing: the complex model

### 2.3 A WG example

Now, based on the model of links and models of nodes we can draw the wavelength graph for a simple network.

In Figure 7 two OADM nodes can be seen where the traffic can be added or dropped. There is an OEXC s well that connects the two rings. This is the model of a part of the network presented in Figure 1.

The number of the wavelength channels and the set of wavelengths of these channels is assumed to be equal for all fibers. Each link consists of two fibers carrying information in opposite directions. Without loss of generality for simplicity reasons the capacity of each wavelength channel is assumed to be equal as well.

### 3. Path Protection

We have assumed end-to-end path protection at the upper layer. For each working path we assume a protection path as well, that does not have any common link or node with the working one. This means that the working and protection paths may not use a physical link or node simultaneously. We assume here protection at the upper layer only, where the certain λ-paths are not protected within the optical layer, but
the demands are protected at the upper layer between its end-nodes. The advantage of this approach is that it needs less resources than protection at the lower layer. This approach is particularly advantageous when shared protection [12] is used, i.e., if working paths of two demands do not have any common element their protection paths may share the capacity of links that is allocated for protection. Clearly the largest demand will determine the capacity for shared protection, unless the working paths of those demands have common elements as well. If they have, their sum will determine the capacity to be allocated for shared protection provided that this sum is larger than the certain demands. This will be referred to as shared protection. As a reference we evaluate dedicated protection as well, where along the protection path the same bandwidth is allocated as for the working one.

4. Problem Formulation

The input is the topology of the graph, the number of \( \lambda \)s over that physical link, the capacity of each link, the type of certain nodes with the pairs of cost values for all internal links and the static traffic matrix. The traffic matrix is assumed to consist of bandwidth requirements of all node-pairs. These are estimated values for aggregated traffic.

The output is the system of \( \lambda \)-paths and the routes of traffic demands over it.

The objective is to satisfy all these demands in the most cost efficient way in the sense of costs assigned to \( \lambda \)-links and internal links of node models. Changing the cost structure of the edges in the WG we can

Figure 7. The graph model of a part of the network shown in Figure 1 with 2 OADM and 1 OEXC node.
change the objective of optimisation. For example either the electrical processing or the optical resources can be prioritised during the optimisation process. One additional constraint is that we want to satisfy all the demands simultaneously, and also to ensure protection for all these demands.

We investigate the case without protection with dedicated protection and shared protection.

It is algorithmically very complex to obtain globally optimal solution for the above formulated problem. It belongs to the class of NP-hard problems [13], since the static routing and wavelength assignment problem, which is a special case of this problem has been shown to be NP-hard [14].

5. Solution Alternatives

The above problem can be formulated as an Integer Linear Program (ILP) and it can be solved by any available ILP solver. Unfortunately, even without any protection it works for networks consisting of less than 10 nodes with no more than 3 λ's [15].

Our algorithms are based on those presented in [16]. We have implemented both, the serial and parallel methods. In case of the ‘serial’ method the whole problem is decomposed to a series of alternative shortest path searches (and allocations) followed by edge-weight adjustments. In the case of the parallel method we decompose the problem into a series of shortest path searches, however, we do not allocate the whole path for a demand, but one link only. Then we adjust the edge-weights and then search again for a shortest path for a demand between the terminal nodes of the partially built path. We call it parallel, since for all the demands it builds their paths link-by-link, randomly. It seems like the paths are not built one-by-one, but different paths parallely, link-by-link. In our evaluations of grooming without protection, with dedicated protection and with shared protection we use the parallel method.

6. Numerical Results

The code has been written in C++ under Linux and Windows operating systems on two computers: an MSI K7Dual AMD Athlon 2000+ MP with 2 Gbytes of RAM and an Intel Pentium 4 with 256 Mbytes of RAM.

The test network was the COST 266 European reference Network [17] shown in Figure 8, while for the impact of the network size onto the problem complexity, networks ranging from 25 to 100 nodes with number of λ-channels per link ranging from 20 to 150 were used. This resulted in
1625 to 9625 vertices in the wavelength graph. Figure 9 and 10 show the running time and the required amount of memory, respectively, required for WGs of different size. Note, that the range of figures differs, and the scale is not linear. It can be seen, that both, the running time and the required amount of memory grow considerably, as the problem grows. If instead of dedicated protection shared protection is used, the memory consumption has increased by about 50% while the running time about 5 times for the 25-node European reference network. This is due to numerous embedded cycles needed for recalculating capacity sharing that follows the routing of each demand one-by-one.

Figures 11 and 12 show the average length of working paths and shared protection paths respectively as the number of λ-channels per link grows from 20 to 100. The curves denoted by numbers from 2-10 represent the cases when the bandwidth of demands grows in such a way, that one λ-channel can accommodate first 10 demands up to the case when only two demands can fit into it.

In contrast to Figures 11 and 12 that show the average wavelength hop count, Figures 13 and 14 show the average physical hop count. In all these cases dedicated protection has been assumed.
Figure 9. Running time for networks of different size for the case of Dedicated Protection.

Figure 10. Memory usage for networks of different size for the case of Dedicated Protection

Figure 11 shows the number of lambda hops, in other words the number of points where the demands have to change the lambda paths either for wavelength conversion or grooming purposes. This will be required whenever the number of $\lambda$s is not sufficient to accommodate all the demands by an exclusive end-to-end $\lambda$-path. It can be seen (Figure 11) that the number of $\lambda$-path changes along a path drops as the number of wavelengths increases. This was expected, since there will be an increasing number of demands that do not need to change the $\lambda$-path but can be routed directly, or if not, a low number of hops is required only. A very similar tendency can be seen for the paths that ensure the shared protection for the demands (Figure 12). The difference is, that the protection paths will always need a slightly larger number of $\lambda$-hops. It can be seen that the curves in (Figure 12) are shifted by 0.2 compared to that in Figure 11.
Figure 11. Wavelength hop count of working paths for different λ-channel capacities as a function of the number of λ-channels.

In both, Figures 11 and 12 it can be seen, that if the bandwidth of demands is low, e.g., when 10 demands can be groomed into a single λ-path, then 20 λs are sufficient to route all the demands with their protection. However, when the bandwidth of demands grow, e.g., when only three or two demands can be groomed into a single λ-path, then respectively 50 or 70 λs are required to satisfy all the demands with their shared protection. Note, that these values may contain a quantization error between -4 and -1, since the evaluation was carried out with a wavelength increment of 5 wavelengths! For the case when no grooming was allowed at all, the number of required wavelengths per link was between 156 and 160 including these values (this part was not included in figures!).

The shown results support, that a significant number of wavelengths (λs) per link can be saved when grooming is employed. The number of λ-path changes drops as the number of λs per link increases.

When higher number of demands can be groomed into a single λ-path, lower number of λ-hops is required. However, as the number of λs per link increases, the situation changes! This is due to the cost-function used, and due to the decomposition of the problem to a sequence of shortest path searches, that force the demands to be groomed even if
it is not necessary. Therefore, the paths will be longer, since they will rather use already built λ-paths, than set up a new, own λ-path. This results a higher λ-hop count.

A method that finds global optimum would probably result about the same (slightly lower) λ-hop count for higher λ as per link values regardless of the limit on the number of demands that can be groomed. It is expected, that the curves will not cross.

Figures 13 and 14 represent the average physical hop count, i.e., the average number of physical links used by certain demands. It can be seen, that in general the paths become shorter as the number of wavelengths increases. However, there can be seen an irregular behaviour for the working paths. For the first λ that yields solution considerably short paths are found. Then, the length of paths first increase, then again decrease and after converges to a steady value.

The reason for this is that during the optimisation process the wavelength changes dominate, not the length of the paths. When the number of wavelengths is low, practically all the wavelength paths are of 1 physical hop length. Therefore the paths will be quite short. As the number of wavelengths grows, the wavelength paths will become longer. This will increase the physical length of the paths. When practically all demands

Figure 12. Wavelength hop count of shared protection paths for different λ-channel capacities as a function of the number of λ-channels.
are accommodated by a single wavelength path, the physical paths will become again shorter. Still, some of the wavelength paths will not use their shortest path, because a wavelength of a link may be already occupied. This behaviour can be particularly well seen for the case when 3 or 4 demands can be groomed into a single λ-path.

It is interesting, that for the protection paths this effect is negligible (Figure 14) compared to that for working paths Figure 13).

Figure 15 shows the relative number of λ-links used (utilisation) as the number of λs grows. Although the utilisation drops linearly, it is relatively slow. For example, while for the utilisation of 91% 20 λs are required, for half of that utilisation (46%) 95 are needed. The explanation is, that the traffic spreads to multiple λ-links as the number of λs grow. In other words, if the demands are not forced by the low number of λs to be groomed, they will be less groomed.

Figures 16 and 17 compare the wavelength hop count and the physical hop count for the dedicated (light line) and shared protection (dark line) for a 16 node network.

It can be seen that for dedicated protection at least 8 λs are needed, while for the shared protection 5 are sufficient.
For the case of shared protection over 20% less wavelength hops are needed (Figure 15) than for the dedicated, while the physical length (hop count) is typically always higher (Figure 16).

7. Conclusion

In this paper we have investigated the impact of grooming onto simultaneous demand routing and static wavelength routing in two-layer networks. We have considered the cases of no protection at all, dedicated protection and shared protection.

Grooming allows finer granularity of the capacity of λ-channels, this leads to better resource utilisation, i.e., less wavelengths are sufficient for the same requirements. The drawback of grooming is, however, that the upper layer must be unique, to be able to perform grooming, and some additional latencies may appear through packet re-multiplexing.

The Wavelength Graph model allows changing the objective of the optimisation. E.g., if we do not want to minimise the amount of grooming, but we prefer to minimise the physical length of the paths, the edge-weight structure should be changed only.
Figure 15. Utilization of λ-links for different λ-channel capacities as a function of the number of λ-channels.

Figure 16. Wavelength hop count for dedicated and shared protection.

The “lesson learned” is, that even for a network of a moderate size (25 nodes) a considerably large number of wavelengths per fiber is required if no grooming is supported. This number further grows (to 160 in our case), if shared protection is required as well. This number further grows if dedicated protection employed.
Figure 17. Physical hop count for dedicated and shared protection.

8. Acknowledgments

This work has been done within the research co-operation framework between Ericsson and the High-Speed Networks Laboratory (HSNLab) at the Department of Telecommunications and Telematics, Budapest University of Technology and Economics. The authors are grateful to Miklós Boda (Ericsson) and Tamás Henk (HSNLab) for their support.

This work is a part of the Hungarian contribution to the European research cooperation project COST 266.

This work has been supported by ETIK http://www.etik.hu.

The second author has been supported by ÓTKA grant D42211 and János Bolyai Postdoctoral Foundation.
References


