Lightpath Configuration of transparent and static WDM Networks for IP Traffic

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Abstract—This paper describes an approach for the optimal configuration of lightpaths in transparent and static WDM networks for IP traffic. The approach involves finding the virtual topology for IP demands and a routing and wavelength assignment (RWA) on the WDM layer. The problem is split into several subproblems and solved by heuristic algorithms.

I. INTRODUCTION

The persistent exponential growth of bandwidth demand in IP backbones drives the introduction of the WDM technology in today’s fiber networks [1]. The first architectures are emerging using optical crossconnects (OXCs) to interconnect IP routers, which communicate over lightpaths [2] with each other. Intermediate multiplexing layers such as ATM or SDH are omitted, such that the whole available bandwidth of the lightpath is available [1].

Given the bandwidth demands between IP router sources and destinations a feasible and efficient (static) configuration of the lightpaths is needed. This is referred to as finding an optimal virtual topology seen by the IP layer and a routing and wavelength assignment (RWA) on the WDM layer.

In this paper we split this problem into several subproblems and solve these by heuristic algorithms. As laser sources currently constitute a large portion of the network element costs, we are interested in using as few sources (and thus lightpaths) as possible.

In the considered architecture the OXCs are interconnected by fiber pairs, one for each direction (see Fig. 1). For each fiber the wavelength constraint has to be fulfilled. An OXC is further connected to at most one IP router, which is the source and sink for at least one lightpath. We assume that the originated and terminated lightpaths can be selected from a set of wavelengths (transponders or colored interfaces). As we do not consider wavelength conversion at WDM nodes, an originated lightpath retains its wavelength.

Two routers become neighbors by a bidirectional virtual link which is formed by two lightpaths for each direction offering the same amount of bandwidth capacity, e.g. 10 Gbit/s Packet-over-SONET point-to-point systems. As depicted in Fig. 1 the two contradirectional lightpaths need not necessarily to have the same wavelength.

Interconnected routers operate using a routing protocol. Today, routing protocols are shortest path based such as OSPF [3]. As IP packets experience a delay at routers, the number of router hops should be restricted. We consider this by allowing only a maximum number of virtual links on the shortest path of a source-destination pair.

We also restrict the amount of transit traffic through IP routers, in order to avoid overwhelming the router (also causing augmented delay for packets). An IP router has also a limited number of line ports (thus the number of virtual links are limited at the node) which we do not consider explicitly.

Of course, the offered total network load has to be carried. We assume here that we are given a demand matrix with bandwidth entries. Each entry is lower or equal than the maximum capacity of a lightpath. In non-synchronous multiplexing environments which holds for IP we may add some margin to the demand entries.

In the following we present the solution approach, explain the virtual topology and RWA algorithms, exemplify the application on a network example and finally draw some conclusions.

![Network Model](image-url)
II. SOLUTION APPROACH

Due to the RWA problem alone the whole problem becomes too complex to be solved by means of integer linear programs [1], [2]. Therefore we divide the problem into subproblems according to Fig. 2 and solve each by heuristic algorithms.

![Fig. 2. Solution Steps](image)

In the first step we find a virtual topology such that the number of (virtual) links is minimized and the given IP demand carried. Minimizing the virtual links corresponds to minimizing the lightpaths demanded from the WDM layer and thus the laser sources. The heuristic algorithm for this is explained in Section III.

In the next step we route the lightpath demands in the optical network composed of the OXCs and fibers. A shortest path algorithm is used for this.

In the last step we have to assign wavelengths to the paths taking the wavelength constraint in fibers and the wavelength continuity constraint in OXCs into account. The approach for the wavelength assignment is explained in Section IV. In general one is given a set of wavelengths which can be used network-wide, thus it is sufficient to obtain one feasible assignment.

The wavelength assignment problem is related to the graph coloring problem [2]. Efficient graph coloring algorithms exist, which do not only perform a color assignment but also minimize the number of colors (which is equal to the number of wavelengths). We used this optimization approach for the wavelength assignment, in order to provide efficient wavelength utilization throughout the network. It must be noted that there may be cases where the minimum number of colors obtained exceeds the cardinality of the wavelength set given through the system.

III. FINDING THE VIRTUAL TOPOLOGY

For the virtual topology algorithm refer to Fig. 3. The aim is to find a virtual topology with minimum number of links such that the bandwidth demand is carried. We further have to assure that the constraints given through the maximum number of hops, the maximum amount of transit traffic and the link capacity are fulfilled.

![Fig. 3. Flow Diagram for the Virtual Topology Algorithm](image)

We start with a virtual topology $G_V$ where for each source-destination pair a link is allocated in $G_D$ if there is a demand between them. This always yields a feasible starting solution.

In the next step we route the demands through the topology obtaining the required bandwidth for each link. Then we try to delete the link with the minimum bandwidth and do the routing process again. If by the deletion of a link one of the constraints is violated, we try another link carrying equal or next less bandwidth. If all links are covered, the algorithm terminates. For the routing we use a shortest path algorithm as in the case of OSPF, with link weights equal to one.

IV. ROUTING AND WAVELENGTH ASSIGNMENT

For each virtual link obtained by the preceding algorithm a path has to be defined on the WDM layer. Although we have a large freedom in choosing a routing, we decided again for shortest path routing with fiber weights set to one. By this, as the number of fibers used by a lightpath is minimal, we best utilize the network fiber capacity. Moreover, the lightpath lengths are kept relatively short to ensure that the signal is not overly attenuated at the receiver.

Once all paths are routed in the WDM network $G_P$ we have to assign wavelengths to them. For this we construct a path graph $G_C$ by adding a path-node for each routed path in $G_P$. If two lightpaths share the same fiber in $G_P$, the path-nodes in $G_C$ are connected by an edge. The path graph for the network in Fig. 1 is depicted in Fig. 4.
Now we can solve the graph coloring problem [2] on $G_C$, which tries to assign colors to the nodes in such a way that adjacent nodes do not have the same color and the total number of used colors is minimized. In the example of Fig. 4 this is accomplished by two colors. Once we have the colors of each path-node in $G_C$, we associate different wavelengths to each color. Then we can go back to the corresponding paths and assign these wavelengths to them.

One efficient algorithm for the graph coloring problem is the Degree of Saturation (DSATUR) algorithm [4] depicted in Fig. 5.

![Flow Diagram of the DSATUR Algorithm](image)

Denote “the degree of saturation” as the number of colors that are not allowed for a node, because adjacent nodes have already obtained these colors. For each node these colors are stored in an ordered label list. In the first step of an iteration we consider all uncolored nodes which have the maximum degree of saturation (which is zero at the beginning for all nodes). Out of these nodes we take a node with the maximum number of connected edges to this node. We assign the first available color to the selected node which is not contained in the label list. This selected color is then added in the label list of each neighbor. Then all adjacent edges are deleted and the next iteration starts. If all nodes are colored, the algorithm stops.

V. NUMERICAL RESULTS

We used the described approach to configure the topology of the NSF network (14 nodes, 21 links) used in [5], where we associated each link with a fiber pair and each node with a router connected to an OXC. We also used the traffic matrix in [5] scaled such that the entry with the maximum value equals 10 Gb/s, yielding a total network load of 120 Gb/s. The bit rate capacity of a wavelength was set to 10 Gb/s.

Using the algorithms we obtained the following results. Due to the heuristic approach the execution time for each run is in the order of seconds.

In the case of no constraints on the number of hops and the forwarding traffic we obtain 19 virtual links (this is half of the number of laser sources) and 4 wavelengths. The number of 19 virtual links is close to 13, the minimum number of links needed to connect the network. The utilization of the wavelengths is half of the capacity. This is still reasonable, since many demand-pairs in [5] carry much more traffic in one direction than in the other. Moreover, all nodes have to be connected, even those which do not source or sink much traffic.

Fig. 6 depicts the characteristic of the number of virtual links and the number of wavelengths when restricting the maximum number of allowed IP hops in the virtual topology algorithm. Both functions are decreasing monotonously and from 1 hop to 2 hops, the function graphs drop down very much, since IP multiplexing becomes possible.

The situation without restrictions on the number of hops but considering a maximum allowed transit traffic through IP nodes for the number of virtual links and the number of wavelengths is shown in Fig. 7. Again both functions are decreasing monotonously and good results are already achieved with an allowed forwarding traffic of 10 Gb/s. Increasing the forwarding traffic from 2 Gb/s to 5 Gb/s decreases the number of links by 9, however, we do not obtain an improvement in the number of wavelengths.

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Fig. 8 depicts both functions over the maximum allowed forwarding traffic using a full mesh demand matrix where each demand-pair requires 1 Gb/s. The functions decrease between zero and 20 Gb/s allowed forwarding traffic. For 20 Gb/s and higher the number of virtual links vary around a value of 25.75, which is due to the heuristic nature of the virtual topology algorithm, and the number of wavelengths does not necessarily decrease anymore. Between 20 Gb/s and 40 Gb/s the number of wavelengths is even reduced, although the virtual links are augmented—but for the RWA the virtual
Fig. 6. The number of virtual links and the number of wavelengths as a function of the maximum number of allowed IP hops for the scaled traffic matrix of [5].

Fig. 7. The number of virtual links and the number of wavelengths as a function of the maximum allowed transit traffic through IP nodes for the scaled traffic matrix of [5].

topology changed. Thus the restriction on the forwarding traffic can be used as a parameter for the heuristic algorithms to obtain result alternatives.

A full mesh demand matrix with equal entries does not reflect the situation of the current Internet accurately, since commonly there is more traffic to and from a node interconnecting to other networks. In order to consider this, we adjusted the traffic matrix such that source-destination pairs containing a chosen interconnection node (node 5 from [5]) have an entry of 8 Gb/s instead of 1 Gb/s. Without restrictions we obtained a capacity utilization of 64%, 37 virtual links and 11 wavelengths.

VI. CONCLUSIONS

In this paper we presented a heuristic algorithm approach to solve the optimization problems of finding a virtual topology for the IP layer and a corresponding routing and wavelength assignment on the WDM layer. The simple heuristic virtual topology algorithm produced already reasonable results. Moreover, enhancements can be achieved by varying the IP routing weights. The DSATUR algorithm for the graph coloring performed well, however, optimizations for the routing on the WDM layer are pursued. As link survivability can be supported efficiently on the WDM layer, disjoint lightpaths can be introduced for redundancy. While in this paper routers do implicitly wavelength conversion, we are planning to consider wavelength conversion explicitly, too.

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Fig. 8. The number of virtual links and the number of wavelengths as a function of the maximum allowed transit traffic through IP nodes for a full mesh traffic matrix (1 Gb/s entries)

REFERENCES


