

Optical Communications

Efficient multi-layer traffic grooming in an IP/MPLS-over-optical network

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SUMMARY

Traffic grooming in meshed optical networks is an important research topic due to the vast difference between the bandwidth requirements of IP/MPLS traffic demands and the capacity of a wavelength. In this paper, we present, evaluate and compare several traffic grooming strategies for a multi-layer IP/MPLS-over-meshed optical network, which take into account the unidirectional nature of IP. Applying a proper multi-layer grooming algorithm also implicates designing a cost-efficient IP/MPLS topology suited for the offered traffic. This study shows that a very promising traffic grooming strategy is the one that deploys a sophisticated capacity installation algorithm in combination with the idea of charging the IP/MPLS layer for the capacity it consumes in the optical layer. Such an iterative, charging-based approach allows significant savings in the overall network design cost compared to a more simple approach. It also allows gradually installing extra line-systems in the optical network as traffic increases. Copyright © 2005 AEIT.

1. INTRODUCTION

The introduction of wavelength division multiplexing (WDM) in the optical network has opened a tremendous amount of bandwidth. Line-systems can transport 160 wavelength channels of 2.5 or 10 Gbps each on a single fiber [1], and research on 40 Gbps channels is ongoing [2]. Due to the importance of data traffic, the future transport network scenario is envisaged to be IP/MPLS-directly-over-optical. With the introduction of optical cross-connects (OXC) in the optical network it becomes possible to establish a lightpath from origin to destination IP/MPLS router of the traffic flow, thus keeping the traffic in the optical domain from start to end. However, there is a vast difference between the typical bandwidth requirement of an IP/MPLS traffic demand (in the range of 155–622 Mbps [3]) and the capacity of a wavelength, which necessitates the efficient sharing of the capacity of a wavelength by multiple IP/MPLS traffic flows.

This is where traffic grooming (sometimes also called optimized consolidation) comes into the picture. Traffic grooming tries to achieve a compromise between the efficient use of the transmission equipment in the optical-network layer and the transit demand through the routers in the IP/MPLS layer. This is schematically explained in Figure 1. Figure 1(a), more wavelengths than necessary are used in the optical transport network (OTN), and they will have a quite low filling. Figure 1(b), on the other hand, lies an unnecessary high burden on the IP/MPLS routers, as in every network node the traffic is passed from the optical layer to the IP/MPLS layer, processed and, if not terminated in that IP/MPLS router, passed back to the optical layer. In Figure 1(c) the right trade-off between wavelength channel usage and IP/MPLS router load is achieved: the wavelengths are properly filled, and no unnecessary transits to the IP/MPLS layer are made. This is what is understood by traffic grooming.

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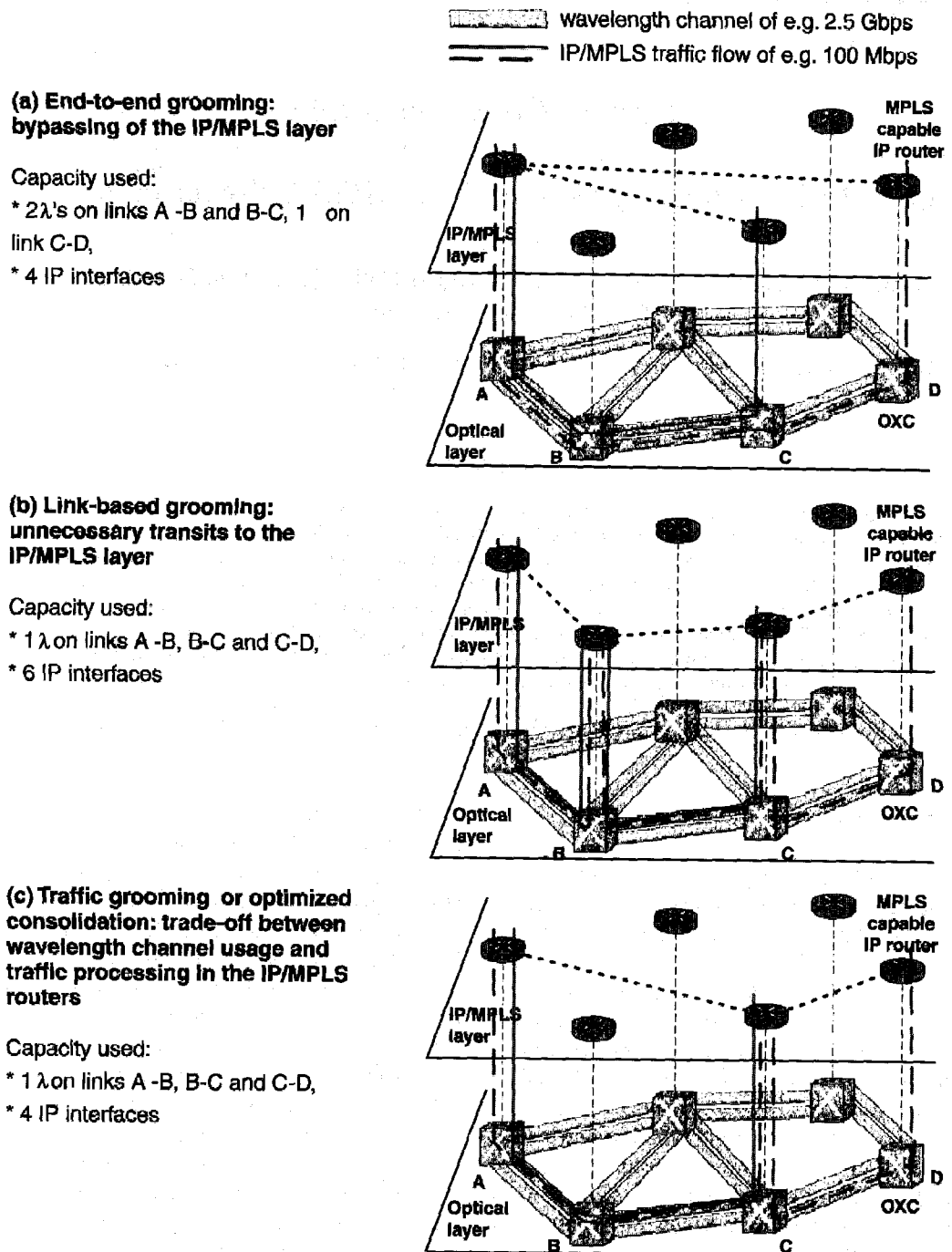


Figure 1. The principle of traffic grooming.

The goal of an efficient multi-layer traffic grooming algorithm is thus to minimize the overall network cost and use the network resources as efficiently as possible. But grooming is more than the routing and grouping of IP/MPLS traffic streams in wavelength channels. Groom-

ing also includes the topological design of the networks themselves [4, 5]. An appropriate IP/MPLS-over-optical traffic grooming algorithm allows designing an optimized logical IP/MPLS topology, and using a candidate physical topology in the most advantageous way.

In literature, the topic of grooming has already been studied quite extensively, but most of the work concentrated on ring-based networks [6–11]. References [12, 13] give an excellent overview of traffic grooming in WDM-based networks. Research on grooming in meshed optical networks, the subject of this paper, has been conducted, but only to some extent (e.g. References [14–16]).

Furthermore, most of the conducted work focused on grooming in a SDH/SONET-over-optical network scenario. Input to the grooming algorithm are the bidirectional and symmetric traffic demands expressed in a number of STM-Xs (where X is e.g. 16 (2.5 Gbps) or 64 (10 Gbps)). The traffic requests thus have the capacity of an entire wavelength channel, and have to be groomed into lightpaths. In this paper, we assume connection requests with a bandwidth that is a fraction of the capacity of a wavelength channel, which is closer to today's reality. Also the study presented in Reference [16] used this assumption, but there the goal of the traffic grooming algorithm was to maximize the total throughput, while we focus on minimizing the total network cost. The algorithm discussed in this paper is a two-layer grooming algorithm as grooming takes place both at the IP/MPLS and the optical network layer. The IP/MPLS traffic demands have to be groomed into the lightpaths, the links of the logical IP/MPLS layer and the resulting wavelength channels have to be groomed into the line-systems.

Besides this, in the much-studied SDH/SONET-over-optical network scenario the client layer is designed to transport mainly voice traffic, which is bidirectional and symmetric[†] in nature. Our work takes into account that voice traffic is no longer the dominant traffic type, but has been overtaken in importance by data traffic, which is unidirectional.[‡] The client layer is an IP network with MPLS functionality and the traffic that is offered to this IP/MPLS network can be unidirectional. Even more, the discussed grooming algorithms are able to handle asymmetric traffic demands,[§] which is crucial as IP traffic gets dominant and several applications transported as IP traffic (with HTTP-based traffic as the much quoted example) send more traffic in one direction than in the other [17].

In this paper, we study the static traffic grooming problem. We do not take into account the dynamic character of the traffic on a short time scale (e.g. diurnal or weekly variations), but only study the influence of the continuous increase in traffic offered to a transport network over a

period of several months or years. In dynamic traffic grooming, also referred to as multi-layer traffic engineering, these small-scale variations are handled by enabling the IP/MPLS client layer to automatically request to establish and/or release lightpaths in the optical network. Generalized multi-protocol label switching (GMPLS) [18] and the automatic switched optical network (ASON) [19] are the paradigms enabling this. Each new traffic demand will, if possible, be grouped (along a part of its route) in an already established lightpath. If this turns out to be impossible, a new lightpath will be established for this traffic demand. Extensive study on dynamic grooming is ongoing (e.g. References [20–23]). Dynamic traffic grooming strategies have to work on-line and, thus, need to be sufficiently fast. A static grooming algorithm can be seen as a more sophisticated off-line grooming approach, that can obtain a result close to optimality and that can steer the capacity-efficiency of the network in a good direction, complementing the real-time dynamic traffic grooming.

The structure of this paper is as follows. In Section 2, the multi-layer traffic grooming problem that we try to solve in this paper is formulated. Section 3 discusses the assumed network architecture of the transport networks. In Section 4, a number of methodologies used to tackle the multi-layer traffic grooming problem are explained. Section 5 introduces a practical case study on a realistic network in which these different multi-layer traffic grooming algorithms are compared. Subsection 5.2 focuses on multi-layer traffic grooming under asymmetric IP/MPLS traffic demands. Finally, the conclusions are formulated in Section 6.

2. PROBLEM FORMULATION

The multi-layer traffic grooming problem that we want to solve in this paper can be formulated as follows:

Given:

- a candidate physical topology consisting of a number of nodes where IP/MPLS routers and OXCs can be installed and a number of bidirectional links (fibers) interconnecting these nodes,
- a traffic matrix which serves as input to the IP/MPLS layer (this traffic matrix contains unidirectional and maybe asymmetric traffic).

Find:

- the logical IP/MPLS topology,
- the routing of the traffic demand on this IP/MPLS logical topology,

[†]Both directions of a SONET/SDH traffic flow follow the same route (in opposite direction) and have the same bandwidth requirements.

[‡]Both directions of an IP traffic flow may follow another route.

[§]Both directions of an IP traffic flow may have different bandwidths.

- the routing of the capacity demand from the IP/MPLS layer on the candidate physical topology,

and thus

- the size of the IP/MPLS routers and the OXCs needed,
- the capacity (number of optical line-systems) needed on the optical links.

With the objective of minimizing the overall network cost (IP/MPLS and optical layer). Note that we do not take into account any recovery requirements in our static traffic grooming approach. Adding survivability considerations to a multi-layer traffic grooming approach severely complicates the algorithms, since a recovery strategy should be applied in all layers of the multi-layer network to guarantee recovery from all possible network failures. Special care should be taken to avoid unnecessary waste of capacity by protecting traffic demands both in the IP/MPLS layer and the optical layer, and shared risk link groups (SRLGs) should be considered to make sure that working and protection path in the IP/MPLS layer are also routed completely disjoint in the underlying optical network layer.

3. NETWORK ARCHITECTURE

The transport network architecture assumed in this paper consists of an IP/MPLS logical network layer on top of a meshed optical network layer (see Figure 2). In each node, an OXC and an MPLS capable IP router are installed. One of the goals of the multi-layer traffic grooming algorithms discussed in this paper is to design the IP/MPLS logical topology most suited for the offered traffic pattern, while minimizing the overall network cost. In the optical layer,

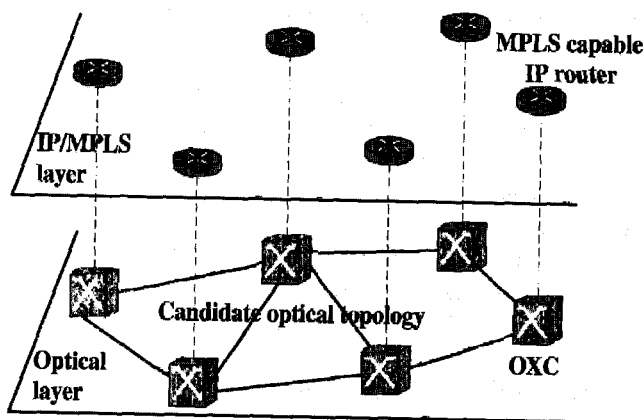


Figure 2. Network architecture.

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we assume that there are a number of candidate optical links present. Together they form the candidate optical topology. By applying a traffic grooming algorithm to the multi-layer IP/MPLS-over-optical network, the topology of the IP/MPLS logical layer will be designed. But also the resulting topology of the optical layer may differ from the candidate optical topology: not all links or nodes in the optical candidate topology have to be used.

The traffic demand offered to the IP/MPLS layer is assumed to be unidirectional and may be asymmetric. This is a quite realistic assumption, as data traffic and especially IP traffic may have an asymmetric traffic pattern. The IP/MPLS layer topology is assumed to be unidirectional (both directions of a logical IP link do not necessarily need to have the same amount of capacity). In the optical layer, however, the same amount of capacity has to be installed on both directions of the optical links.

4. MULTI-LAYER TRAFFIC GROOMING ALGORITHMS

In this section, several approaches to solve the above-formulated multi-layer traffic grooming problem are discussed. Most of them make use of the forward synthesis and design tightening (FS + DT) heuristic that solves the minimum cost capacity installation (MCCI) [24] problem in a single-layer network. The MCCI problem determines the minimal set of fixed-capacity systems that needs to be installed in a single-layer network in order to allow the simultaneous routing of all traffic demands while minimizing the total network installation cost. The FS + DT heuristic deployed in this paper is based on the algorithm described in Reference [25], and introduced in Reference [26]. More information can be found in Appendix A. An alternative for the FS + DT algorithm is a simple shortest path (SP) routing.

The FS + DT algorithm could be used consecutively in the IP/MPLS and optical network layers to solve the traffic grooming problem. However, as our goal is to minimize the overall network cost, and not the network cost of both layers separately, some kind of feedback loop between the IP/MPLS layer and the optical layer is required. The feedback approach used in this paper is based on the idea of charging the IP/MPLS logical layer for the resources it uses in the optical layer (see Figure 3), as was suggested in Reference [25]. There are however some important differences with Reference [25], for example the client layer is now a unidirectional IP/MPLS network that needs to accommodate the unidirectional and asymmetric IP traffic

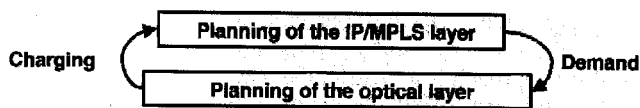


Figure 3. The IP/MPLS logical layer is charged for the resources it uses in the optical layer.

demand [17], and a different feedback loop is applied (see further).

The multi-layer traffic grooming algorithms described in the remainder of this section differ in the way the capacity installation problem is solved (using SP routing on a fixed topology or applying the FS + DT heuristic), the way in which information is fed back from the optical layer to the IP/MPLS layer and in computational complexity. Subsection 4.1 discusses the FS + DT → FS + DT algorithm, which sequentially solves the grooming problem in the IP/MPLS and optical layers using the FS + DT heuristic, without applying a feedback loop. In Subsection 4.2 a feedback loop is added to the algorithm (FS + DT ↔ FS + DT). Several options for this feedback loop are discussed. In Subsection 4.3 a simple SP routing replaces the FS + DT heuristic in the optical layer. No feedback loop can be implemented (FS + DT → SP). In Subsection 4.4, on the other hand, the FS + DT algorithm is replaced by SP in the IP/MPLS layer (SP ↔ FS + DT). Finally in Subsection 4.5 SP is applied in both the IP/MPLS and the optical layer (SP → SP).

4.1. FS + DT → FS + DT

The FS + DT → FS + DT algorithm is a multi-layer traffic grooming approach that makes use of the FS + DT heuristic in both the IP/MPLS and the optical layer. As FS + DT is a quite sophisticated optimization algorithm, and no feedback loop is implemented, a decent solution should be obtained in a limited amount of time. The different steps of the algorithm are:

• Step 1: Problem initialization

The traffic demand is routed on a unidirectional full-mesh network between the IP/MPLS routers. The resulting optical layer traffic demand is then routed on the candidate physical topology along the least cost path. In this first step, the cost of a wavelength on an optical link is simply the cost of a fully capacitated line-system divided by the number of wavelengths this line-system can support (e.g. when a line-system of 40 wavelengths has a cost X, each wavelength will be assigned a cost X/40). This gives a very first estimation of the capacity needed in the optical layer, and more important, allows assigning a cost to the IP/MPLS

links based on the cost for supporting these links in the optical layer (i.e. the feedback information). In our approach, each IP link gets assigned a cost inversely proportional to the filling of the line-systems along its route in the optical layer. An IP/MPLS link that is for instance routed along two consecutive optical links with 40-channel line-systems that are 20% filled, will have a cost of $2 \times ((\text{cost of a line-system})/40) \times 5$. Now the problem is initialized, we can tackle the real traffic grooming problem.

• Step 2: Traffic grooming in the IP/MPLS layer using the FS + DT heuristic

The FS + DT algorithm is applied to groom the traffic demands on the unidirectional IP/MPLS topology. The capacity that needs to be installed on each link and node in order to accommodate all demands at lowest cost is determined. At the end of Step 2, the IP/MPLS layer has been designed taking into account the traffic demand and an estimation of the cost for supporting the logical topology in the optical layer. The traffic demand offered to the underlying optical layer is also determined.

• Step 3: Traffic grooming in the optical layer using the FS - DT heuristic

This optical layer traffic demand is then groomed on the bidirectional optical candidate topology, using the FS + DT algorithm. At the end of this step, the optical layer has been dimensioned. Note that not all links of the physical candidate topology are necessarily used (have capacity installed). At this point, the total cost of the IP/MPLS and optical network design can be calculated.

4.2. FS + DT ↔ FS + DT

The FS + DT ↔ FS + DT grooming algorithm adds a feedback loop to the FS + DT → FS + DT algorithm of Subsection 4.1. This increases of course the computation time (how much depends on the number of iteration loops performed), but allows achieving a cheaper overall network design. The feedback loop is based on a charging scheme: the IP/MPLS layer is charged for the capacity it consumes in the underlying optical layer. Different charging options are explained in Subsections 4.2.1 to 4.2.3.

• Step 1: Problem initialization
do{

- Step 2: Traffic grooming in the IP/MPLS layer using the FS + DT heuristic
- Step 3: Traffic grooming in the optical layer using the FS + DT heuristic
- Step 4: Feedback loop based on a charging scheme

Cost information is fed-back from the optical layer to the IP/MPLS layer in order to improve the overall network cost and the IP/MPLS logical network topology design. Just as in the initialization step, the IP links are charged for using capacity in the underlying optical layer and get assigned a cost proportional to the filling and the cost of the line-systems along their route in the optical layer.

}next iteration

The algorithm then iteratively performs Steps 2, 3 and 4 until it is stopped at Step 3 and the lowest encountered total network cost is determined. After 10–14 iterations, a good solution is usually found.

Several charging scheme options have been investigated. They differ in the fact whether or not the charging factor (CF) for the IP/MPLS links that were not used after the most recent iteration, is reset to zero after each iteration, and in the exact value of the charging factor for the individual links in the IP/MPLS network.

4.2.1. Charging factor of unused IP/MPLS links is reset to zero at each iteration ($FS + DT \leftrightarrow FS + DT$, $CF \leftrightarrow 0$). The IP/MPLS links that are not used (do not carry any traffic) after the current iteration are assigned a cost zero. The other IP/MPLS links (that do carry traffic) are assigned a cost proportional to the filling and the cost of the links along their route in the optical layer.

4.2.2. Charging factor of unused IP/MPLS links is same as previous iteration ($FS + DT \leftrightarrow FS + DT$). Here the IP/MPLS links that are not used after the current iteration, keep the cost of the previous iteration. After the first iteration this algorithm and the one described in subsection 4.2.1 have the same result, but the topology and cost in the subsequent iterations differ.

4.2.3. Charging factor of IP/MPLS links is weighted sum of newly calculated charging factor and charging factor of previous iteration(s) ($FS + DT \leftrightarrow FS + DT$, α). Instead of changing the IP link cost in the sometimes very drastic way of Subsections 4.2.1 ($FS + DT \leftrightarrow FS + DT$, $CF \leftrightarrow 0$) and 4.2.2 ($FS + DT \leftrightarrow FS + DT$), an inertia factor α can be applied. The used CF for an IP/MPLS link is now a weighted sum of the previous CF and the newly calculated one:

$$\text{used CF}_{\text{link } x-y} = \alpha \times \text{previous CF}_{\text{link } x-y} + (1 - \alpha) \times \text{new CF}_{\text{link } x-y}$$

α has a value between 0 and 1 and a different α will result in a different course of the iterative multi-layer traffic grooming algorithm.

4.3. $FS + DT \rightarrow SP$

A third approach is to restrict the use of the $FS + DT$ heuristic to the IP/MPLS network. The optical layer is dimensioned using SP routing on the candidate optical topology. No feedback loop can be deployed here. This approach is more or less similar to the ones suggested in Reference [12][†] and Reference [15] and is denoted $FS + DT \rightarrow SP$. Replacing the $FS + DT$ algorithm by SP routing in the optical layer, and the absence of a feedback loop, significantly reduce the computational complexity and computation time. The resulting overall network cost is however expected to be higher. The different steps of the algorithm are:

- Step 1: Problem initialization
- Step 2: Traffic grooming in the IP/MPLS layer using the $FS + DT$ heuristic
- Step 3: Optical layer dimensioning using a SP strategy

The capacity demand coming from the IP/MPLS layer is routed on the optical layer along the least cost path. At the end of this step, the candidate physical topology (note that all links will have capacity installed) has been dimensioned and the total network cost is calculated.

4.4. $SP \leftrightarrow FS + DT$

Here, the methodology presented in Subsection 4.3 is reversed: SP routing is used in the IP/MPLS layer, while the optical layer is optimized using the $FS + DT$ algorithm. Replacing the $FS + DT$ heuristic with SP again lowers the computation time. The reduction per iteration is even more significant than with the $FS + DT \rightarrow SP$ algorithm, as in the IP/MPLS layer more traffic flows have to be routed than in the optical layer. A feedback loop is used to feed back charging information from the optical layer to the IP/MPLS layer. Applying the $FS + DT$ heuristic only in the optical layer will result in a lower overall network cost compared to deploying this heuristic only in the IP/MPLS layer, since the cost of the optical equipment is dominant. The steps of the algorithm are:

- Step 1: Problem initialization
do{
- Step 2: IP/MPLS layer design and dimensioning using a SP strategy

[†]In Reference [12], the first step consists of designing the IP/MPLS topology with the least number of (fixed-capacity) lightpaths. This is equivalent to minimizing the electronic installation cost in the IP/MPLS layer. This is more or less the same as the $FS + DT$ heuristic. The IP/MPLS capacity demand is then routed in the optical layer using a shortest path (in terms of cost) routing and dimensioning algorithm.

Route all traffic demands along the shortest path in the full mesh IP/MPLS topology (thus, on a direct link).

- *Step 3: Traffic grooming in the optical layer using the FS + DT heuristic*
- *Step 4: Feedback loop based on a charging scheme*

As in Subsection 4.2, different options are possible: the CF of unused IP/MPLS links can be reset to zero or can keep its previous value, and the inertia factor α can be applied.

}next iteration

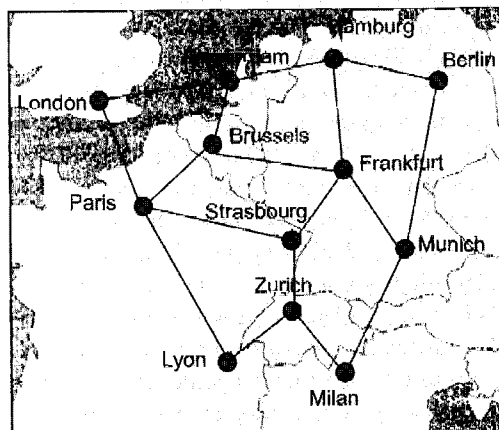
Note that although the starting IP/MPLS topology in Step 2 is always a full mesh, the resulting logical topology (obtained after all traffic is routed on the network) is not necessarily, due to the charging based feedback loop.

4.5. SP \rightarrow SP

A last option would of course be to apply SP routing in both the IP/MPLS and optical layer (SP \rightarrow SP). In this case, little effort is done to efficiently deploy the network facilities but this approach has a very low computation time.

- *Step 1: Problem initialization*
- *Step 2: IP/MPLS layer design and dimensioning using a SP strategy*
In the full mesh IP/MPLS topology, all traffic demand layers are routed along the shortest path.
- *Step 3: Optical layer dimensioning using a SP strategy*

In the candidate optical topology, the traffic demands coming from the IP/MPLS layer are routed along the shortest path. Capacity will be installed on all links of the candidate optical topology. After this step, the overall network installation cost is calculated.



5. CASE STUDIES

In this section, the multi-layer traffic grooming algorithms that were described in Section 4 are compared. Subsection 5.1 compares in detail the performance of the various traffic grooming algorithms under different traffic loads. Part of these results were already presented in Reference [27]. Subsection 5.2 discusses the performance of the most efficient multi-layer traffic grooming algorithm under traffic demands with varying asymmetry.

5.1. Case study I

5.1.1. Network under study. As test network, we have chosen an European optical backbone network, based on the ones described in Reference [28] (see Figure 4). It consists of 12 nodes connected by 17 links in a mesh topology. As said before, in all node locations an MPLS-capable IP router is installed together with an OXC. The traffic forecast for this network (see Figure 4) and the cost model for the IP/MPLS and optical equipment were also taken from References [28–30].

5.1.2. Cost model. The cost model used in this case study [31] takes into account:

- *the line cost:* cost of the fiber (including the cost for e.g. digging the duct) and the optical amplifiers,
- *the WDM line-system cost:* cost of the mux/demux, the amplifiers and the long-reach transponders,
- *the OXC cost:* this cost depends on the size of the OXC needed (we have assumed an opaque OXC design, allowing full wavelength conversion due to the presence of transponders), and includes the cost of the tributary cards and an estimation of the cost of the management system,

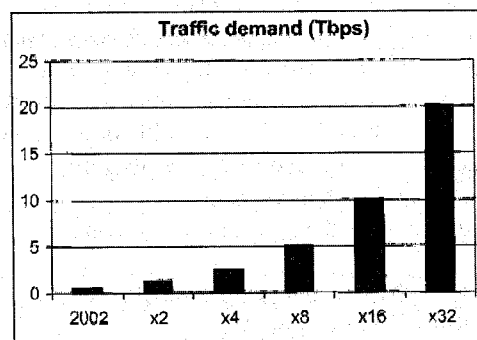


Figure 4. European candidate physical topology and the traffic offered to this network.

- *the IP router cost*: this cost also includes the router line cards.

The line-systems that can be installed in the network can transport 40 wavelength channels of 10 Gbps. Ports were added to the IP routers and OXCs according to the number of in- and out-going lightpaths respectively line-systems.

This cost model is very important, as in a traffic grooming algorithm much of the outcome depends of course on the ratio between the transport cost in the optical layer and the IP/MPLS router cost. We would like to stress that the figures in our cost model are realistic ones, obtained from discussions with European network operators.

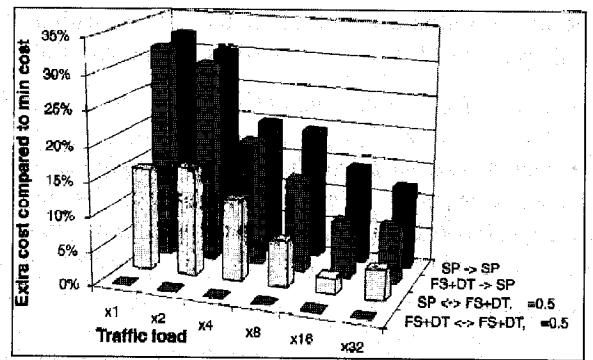
5.1.3. Comparison of the various multi-layer grooming algorithms. In this section, the above discussed multi-layer traffic grooming algorithms are compared. The main performance factor of the algorithms is of course the total cost of the overall network design (IP/MPLS and optical layer). But also the (evolution of the) resulting topologies of the IP and optical layer under increasing traffic load are discussed.

Three sets of comparisons are made. First, in Subsection 5.1.3.1, the increased performance of the multi-layer traffic grooming algorithms that deploy the FS + DT algorithm is demonstrated. Subsection 5.1.3.2 discusses the cost advantage that can be obtained by the introduction of a feedback loop in the traffic grooming algorithm. Finally, Subsection 5.1.3.3 studies the influence of the inertia factor α on the performance of the multi-layer traffic grooming algorithm with feedback loop and deploying the FS + DT algorithm in both the IP/MPLS and the optical layer of the network.

5.1.3.1. Influence of the FS + DT algorithm. First, the influence of deploying FS + DT instead of SP is investigated. Hereto the variations of the algorithm that make use of a simple SP routing, instead of the FS + DT algorithm in the IP/MPLS or optical layers are compared with the algorithm that uses the FS + DT strategy in both the IP/MPLS and optical layer. Where possible, a feedback loop is used, as Subsection 5.1.3.2 will prove that introducing such a feedback loop into the algorithm can significantly improve the obtained result.

Following variations of the algorithm are compared:

- FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$ (see Subsection 4.2.3)
- FS + DT \rightarrow SP (see Subsection 4.3)
- SP \leftrightarrow FS + DT, $\alpha = 0.5$ (see Subsection 4.4)
- SP \rightarrow SP (see Subsection 4.5)



	FS+DT \leftrightarrow FS+DT $\alpha = 0.5$	SP \leftrightarrow FS+DT, $\alpha = 0.5$	FS+DT \rightarrow SP	SP \rightarrow SP
Average	0.0%	9.3%	18.3%	21.4%

Figure 5. Extra cost in % with regard to the minimum network installation cost achieved with these four algorithms.

Figure 5 illustrates the total installation cost of the IP/MPLS and optical layer design obtained with these four algorithms for the increasing traffic demands of Figure 4 (2002 or $x1$ to $x32$). As can be seen, the proposed FS + DT \leftrightarrow FS + DT algorithm with inertia factor $\alpha = 0.5$ performs the best. The most expensive network design is obtained with SP \rightarrow SP, as could be expected, since this algorithm does not perform any real optimization. On average, over all traffic loads, the resulting network design is 21.4% more expensive than the one obtained with FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$. The results obtained with FS + DT \rightarrow SP are somewhat better than the ones obtained with SP \rightarrow SP, but not significantly. The cost of the overall network design has decreased with a few percentages (on average 18.3% more expensive than the one obtained with FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$) as the SP routing in the IP/MPLS layer is replaced with the more efficient FS + DT algorithm. However, as there is no feedback loop, the initial estimation of the cost in Step 1 of the algorithm, the problem initialization step, cannot be improved, leading to a quite poor result. The results obtained with SP \leftrightarrow FS + DT, $\alpha = 0.5$ are on average 9.3% more expensive than the ones obtained with FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$. This clearly shows the advantage that can be obtained by deploying FS + DT instead of SP since both algorithms differ only in the used algorithm in the IP/MPLS layer. They both deploy a feedback loop, and in both cases the inertia factor α has a value of 0.5.

Figure 5 also illustrates that the advantage that can be obtained with an efficient grooming scheme decreases with increasing traffic. This will also be noted in the comparison of Subsection 5.1.3.2. An important remark though

Influence FS+DT algorithm

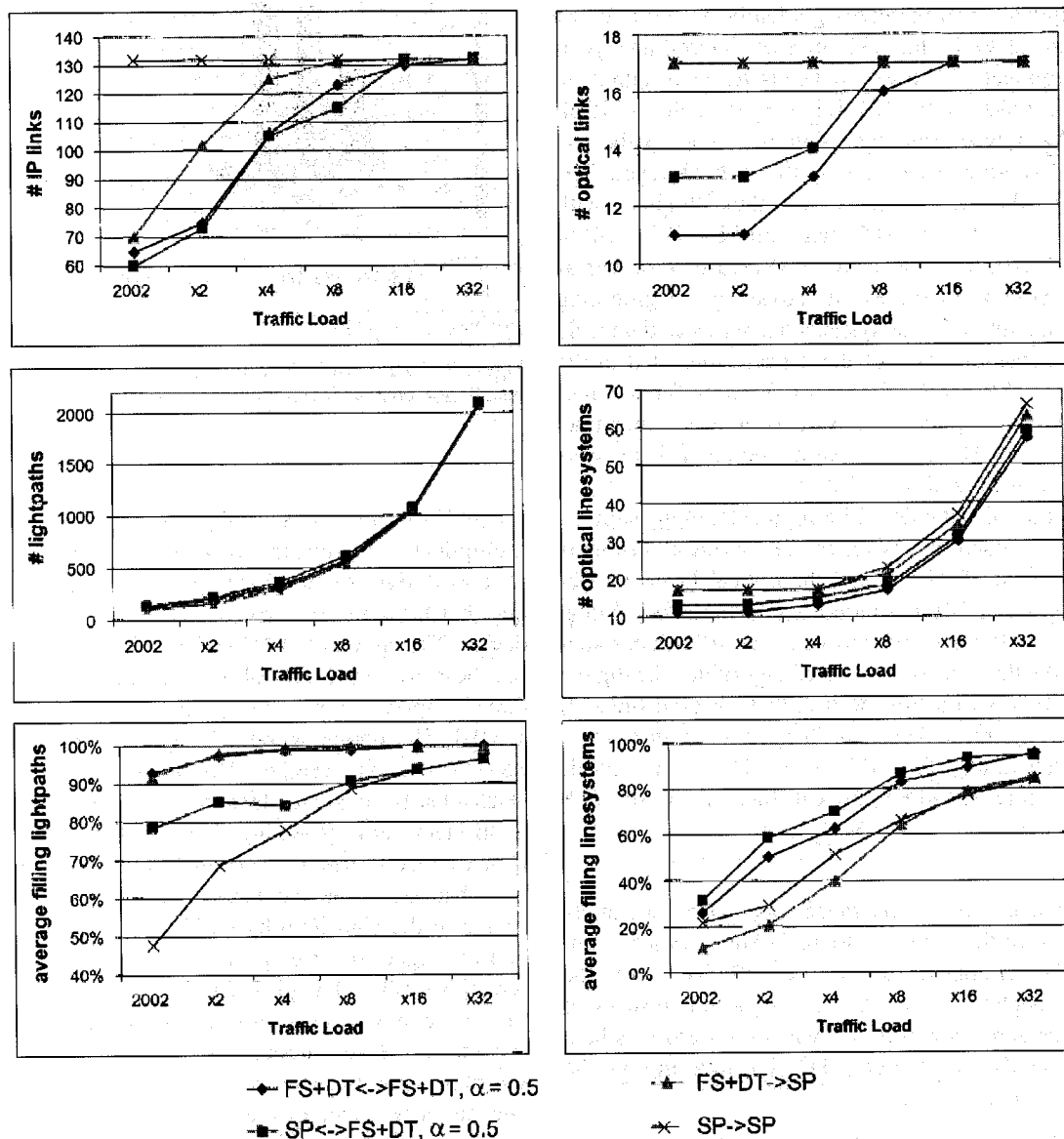


Figure 6. Evolution of the IP/MPLS topology, the use of the optical candidate topology, the filling of the lightpaths and the optical line-systems with increasing traffic.

is that by the time the traffic will have reached a level that is 10 or 20 times higher than the original traffic level, the technology will have further matured and improved, and higher bit rates will be transported over a single wavelength (e.g. transition from 10 to 40 Gbps wavelength channels). This implies that the importance of finding a good solution for the traffic grooming problem will not diminish over time.

This cost difference can be further explained by a number of reasons. Let us first look at the optical layer. Figure 6 quantifies the evolution of the optical layer over time. With FS + DT ↔ FS + DT, $\alpha = 0.5$, the capacity demand coming from the IP/MPLS layer is really groomed into the candidate optical topology, as opposed to FS + DT → SP and SP → SP. This implies that with FS + DT ↔ FS + DT, $\alpha = 0.5$ not all candidate links are actually used. In fact,

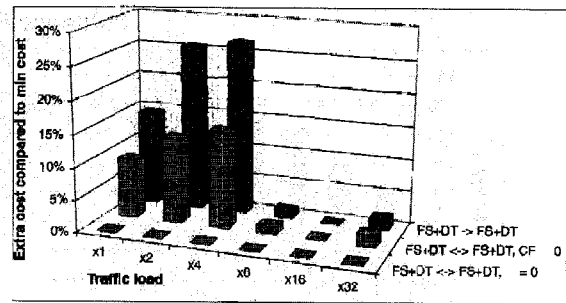
we see that with $FS + DT \leftrightarrow FS + DT$, $\alpha = 0.5$ the number of used optical links increases gradually from 11 for $x1$ (2002) and $x2$ to 17 for $x32$. In each intermittent year, capacity (optical line-systems) needs to be installed on some extra links. With $FS + DT \rightarrow SP$ and $SP \rightarrow SP$, all links are deployed from the beginning, due to the use of the SP routing algorithm in the optical layer. The filling of the line-systems is thus higher with $FS + DT \leftrightarrow FS + DT$, $\alpha = 0.5$ than with $FS + DT \rightarrow SP$ or $SP \rightarrow SP$. This difference in filling decreases however as the traffic volume increases: the advantage of grooming the lightpaths into the line-systems decreases as the traffic demand reaches the level of the capacity installed in the optical layer. $SP \leftrightarrow FS + DT$, $\alpha = 0.5$ needs for a rather small traffic load optical line-systems on more links than $FS + DT \leftrightarrow FS + DT$, $\alpha = 0.5$, but not on all, as is the case for $FS + DT \rightarrow SP$ and $SP \rightarrow SP$.

Besides this, also the IP/MPLS logical topology shows a difference (in evolution). When the SP routing algorithm is used in both the IP/MPLS and the optical layer, the IP/MPLS layer has a full mesh topology from the beginning, as there is a traffic demand between each IP/MPLS router pair. With the three other considered algorithms the logical topology evolves to a full mesh (132 IP logical links**) with increasing traffic, but with $FS + DT \rightarrow SP$ this evolution goes the fastest. $FS + DT \leftrightarrow FS + DT$, $\alpha = 0.5$ needs somewhat more IP/MPLS logical links than $SP \leftrightarrow FS + DT$, $\alpha = 0.5$.

5.1.3.2. Influence of the feedback loop. Next, we study the influence of the feedback loop. In Subsection 5.1.3.1, we already demonstrated the cost-efficiency of the algorithms deploying the $FS + DT$ algorithm instead of the SP algorithm. Therefore, we will limit ourselves here to the options that use the $FS + DT$ algorithm in both the IP/MPLS and optical layer:

- $FS + DT \rightarrow FS + DT$ (see Subsection 4.1)
- $FS + DT \leftrightarrow FS + DT$, $CF \neq 0$ (see Subsection 4.2.1)
- $FS + DT \leftrightarrow FS + DT$, $\alpha = 0.0$ (see Subsection 4.2.2)

Figure 7 shows the extra cost (in %) with regard to the minimum overall network installation cost achieved with these three algorithms. It is clear that the option



	$FS+DT \rightarrow FS+DT$	$FS+DT \leftrightarrow FS+DT$, $CF \neq 0$	$FS+DT \leftrightarrow FS+DT$, $\alpha = 0.0$
Average	11.66%	6.68%	0.00%

Figure 7. Extra cost in % with regard to the minimum network installation cost achieved with these three algorithms.

$FS + DT \leftrightarrow FS + DT$, $\alpha = 0.0$ gives the best result. For all multiplication factors, the extra cost compared to the lowest cost design is 0%, which means that this option is the one that leads in all cases to the minimum cost network design. The option $FS + DT \leftrightarrow FS + DT$, $CF \neq 0$ is the second best: averaged over all considered traffic loads, it is 6.68% more expensive than $FS + DT \leftrightarrow FS + DT$, $\alpha = 0.0$. The option without feedback loop ($FS + DT \rightarrow FS + DT$) is on average 11.66% more expensive. This result clearly illustrates that the feedback loop helps the multi-layer traffic grooming algorithm to reach a low overall network cost when the original estimation turned out to be a bad one. The feedback loop allows adjusting the course of the algorithm by building some memory effect into the algorithm. Resetting the cost of unused links to zero ($FS + DT \leftrightarrow FS + DT$, $CF \neq 0$), results in very capricious successive results: links whose cost was reset to zero become in the next iteration very attractive, steering the algorithm away from the most advantageous overall result. The memory effect in the $FS + DT \leftrightarrow FS + DT$, $\alpha = 0.0$ algorithm is stronger, and takes into account all previous encountered results, in contrast to the $FS + DT \leftrightarrow FS + DT$, $CF \neq 0$ algorithm.

In Figure 7, a distinct difference is also observed between the results for a rather low traffic load ($x1$ or 2002 to $x4$) and a quite high traffic load ($x8$ to $x16$): the advantage obtained with a more efficient multi-layer traffic grooming algorithm decreases as the traffic demand reaches the level of the capacity installed in the optical layer when each optical link would deploy a full-optical line-system. The consecutive iteration loops can, from then on, not significantly improve the results, which lower the influence of a feedback loop.

**In this paper, the following terminology is used: a wavelength channel is a single wavelength on a single optical link. A lightpath is a sequence of (one or) more wavelength channels between the origin and destination nodes. A logical IP link is a link between two IP/MPLS routers in the logical IP/MPLS network layer. A logical IP/MPLS link corresponds to one or more lightpaths between these two IP/MPLS routers.

Influence feedback loop

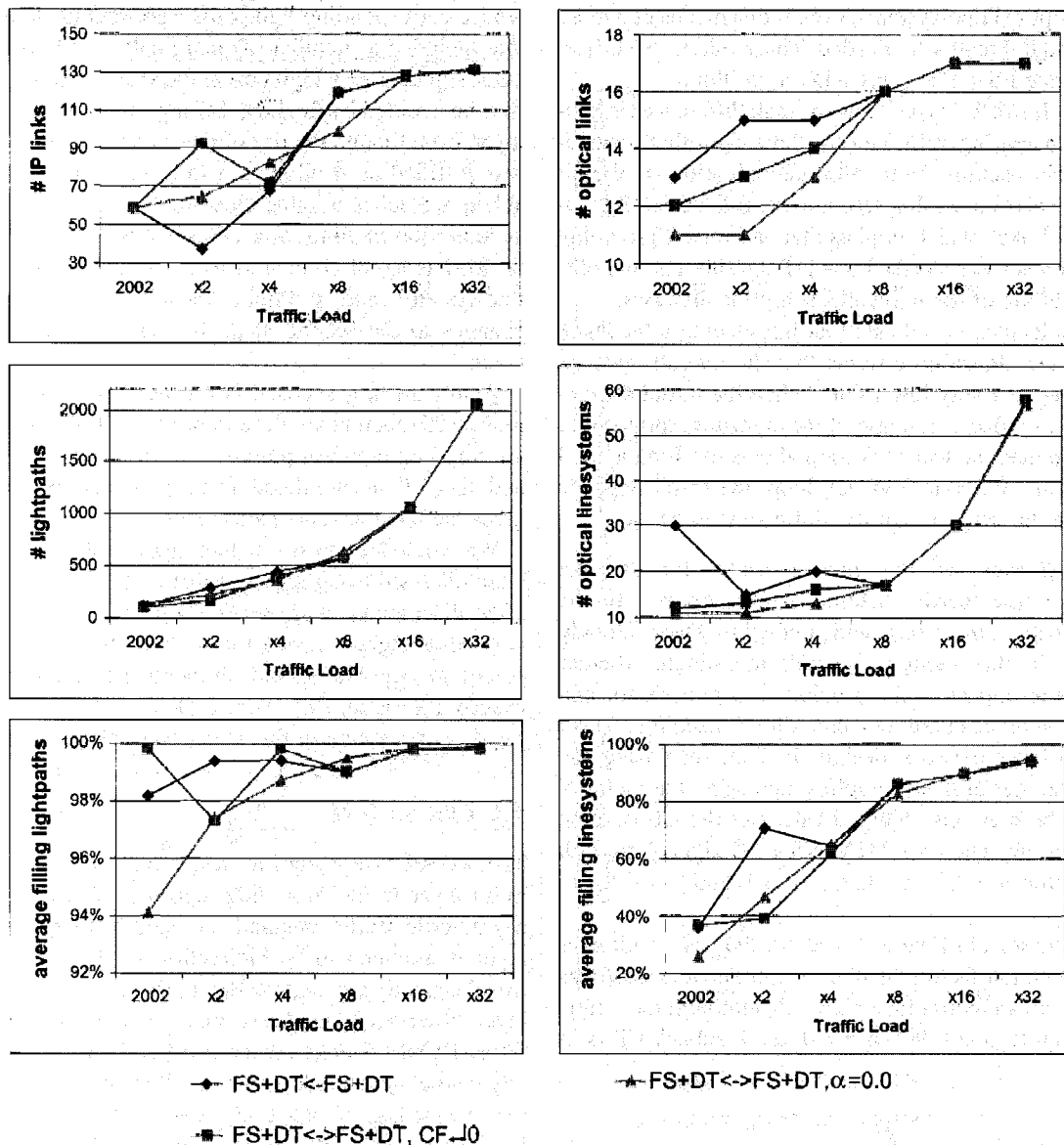


Figure 8. Evolution of the IP/MPLS topology, the use of the optical candidate topology, the filling of the lightpaths and the optical line-systems with increasing traffic.

There are a number of factors that explain the cost difference between the three discussed algorithms. Let's start again with discussing the optical layer. Due to the use of the efficient single layer FS + DT algorithm, not all candidate optical links (17 in total) are used when the traffic load is rather small, as can be seen in Figure 8. For instance, for FS + DT ↔ FS + DT, α = 0.0, the number of used optical links increases gradually from 11 for a multiplication factor of 1 (2002) to 17 for a multiplication factor of 32. For

each intermittent multiplication factor, capacity (line-systems) needs to be installed on some extra links in the optical network. Due to the feedback loop, the grooming of the traffic demands is more efficient, at least for smaller traffic loads (x1 to x4), explaining the difference in number of used optical links between the algorithms with and without feedback loop. As the cost of the optical layer equipment is quite high compared to the cost of the IP/MPLS equipment, the FS + DT ↔ FS + DT, α = 0.0 algorithm

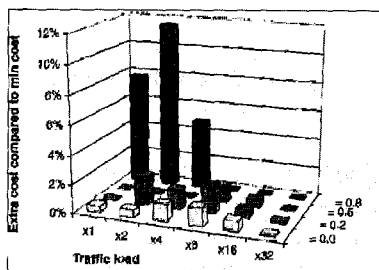
evolves to a solution with quasi-minimum number of deployed optical line-systems, even if this means that more IP links and lightpaths are needed. This explains the difference with the FS + DT \rightarrow FS + DT algorithm.

Also the IP/MPLS layer shows a small difference (in evolution for increasing traffic) for the three algorithms considered in this section. With all three algorithms, the IP topology evolves to a (almost) complete full mesh (132 unidirectional links), which implies that end-to-end grooming is used in most cases. As the FS + DT algorithm is very efficient, the filling of the lightpaths is high in all cases.

The results clearly indicate that introducing a feedback loop into the algorithm ensures that the overall network cost evolves to a very low value. When the initial estimation in the initialization phase of the algorithm turns out to be a bad choice, the feedback loop allows reaching a good overall result. Without feedback loop, the result depends entirely on the first attempt to minimize the cost.

5.1.3.3. Influence of the inertia factor. Finally, the influence of the inertia factor α is investigated. In the previous section, the results with α equal to 0 were already discussed. In this section, we will investigate whether changing the impact of the previous charging factor and the newly obtained charging factor allows reaching a lower cost multi-layer network design. In fact, increasing the value of the inertia factor, implies increasing the memory effect, as the previous obtained values of the CF become more important. The FS + DT \leftrightarrow FS + DT algorithms with inertia factor $\alpha=0.0$, $\alpha=0.2$, $\alpha=0.5$ and $\alpha=0.8$ are compared.

As can be seen in Figures 9 and 10, the best result over all multiplication factors for the overall network cost was obtained with an inertia factor $\alpha=0.5$, although the differences are quite small. When $\alpha=0$, the feedback CF is in



	FS+DT \leftrightarrow FS+DT $\alpha=0.0$	FS+DT \leftrightarrow FS+DT $\alpha=0.2$	FS+DT \leftrightarrow FS+DT $\alpha=0.5$	FS+DT \leftrightarrow FS+DT $\alpha=0.8$
Average	0.69%	1.04%	0.24%	4.04%

Figure 9. Extra cost in % with regard to the minimum network installation cost achieved with different values of the inertia factor α .

some instances a bit too extreme. Logical IP/MPLS links whose corresponding lightpaths were routed along a route that included a (number of) marginally used optical links get assigned a very high cost at the start of Step 2, and will thus be avoided by the FS + DT algorithm in the IP/MPLS layer, even though the use of this expensive IP/MPLS link was justified as it allowed a lower-cost network design. When α reaches a value close to 1, the effect of the CF becomes too small in some cases (especially when the traffic load is small compared to the capacity of an optical line-system) and prohibits meaningful and important changes in the second step, the design of the IP/MPLS layer.

Again, the largest cost differences obtained with the various inertia factors are for a rather small traffic load. Overall, yielding equal importance to the newly obtained CF and the CF accumulated from previous iteration steps gives the most advantageous result.

We would like to stress here again that the cost results were obtained using a very realistic cost model, drawn up after discussions with several European operators. We have also slightly varied the used costs for the different pieces of equipment, and although the results were not exactly the same, they were a close match and the same trends as presented in this paper were observed.

5.2. Case study II

The second case study focuses on how well the proposed multi-layer traffic grooming algorithm can deal with an asymmetric traffic demand. As said before, the optical layer is assumed to be bidirectional. Thus only bidirectional capacity can be installed in this layer. The IP/MPLS layer however is unidirectional, meaning that unidirectional IP/MPLS links are assumed and thus that the capacity on the logical link A-B can differ from the capacity on the reverse logical link B-A. Also the traffic demand that is offered to the network is assumed to be unidirectional (both directions of a single traffic demand may be routed along another path) and even asymmetric (both directions of a single traffic demand have another traffic value).

The influence of the asymmetric character of IP traffic on the cost of the optical network layer has already been studied. The results showed that an increasing asymmetry of the IP traffic resulted in an increasing cost of the optical network layer when that optical network layer was assumed to be bidirectional, at least when the traffic load was high enough compared to the capacity of the line-systems in the optical layer. In contrast, when unidirectional optical line-systems were available, the influence of an

Influence inertia factor

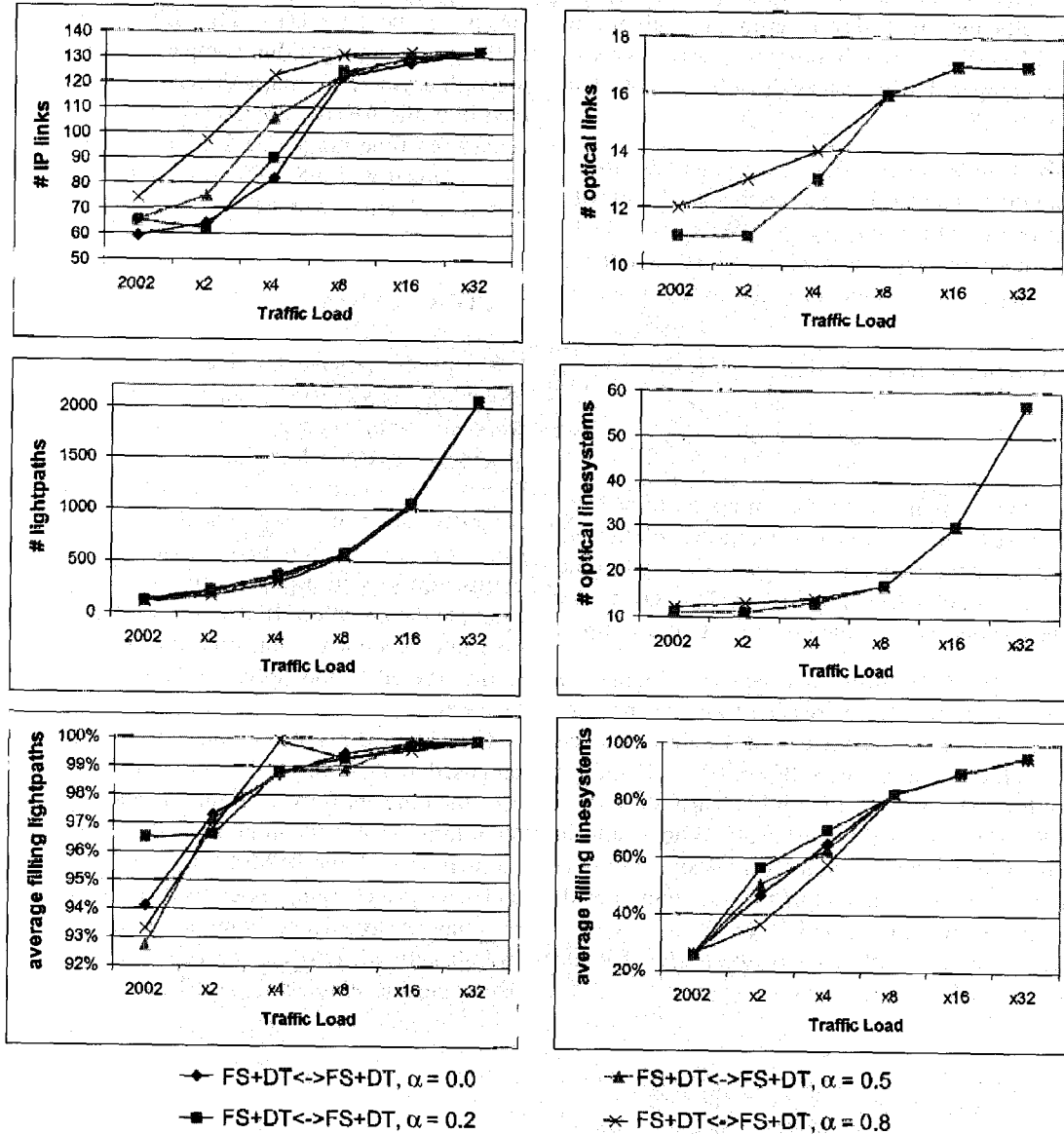


Figure 10. Evolution of the IP/MPLS topology, the use of the optical candidate, the filling of the lightpaths and the optical line-systems topology with increasing traffic.

increasing asymmetry of the IP traffic were almost negligible. However, the study in References [17, 26] used a shortest path routing over a fixed IP/MPLS topology (full mesh in most cases) and a shortest path routing in the optical layer [17] or the FS + DT routing heuristic [26]. No cost-optimizing feedback loop was used to make the network design more efficient and obtain an advantageous

logical IP/MPLS topology. This is exactly the difference with what is investigated in this second case study. Here the IP/MPLS topology best suited to deal with the IP traffic demand is being designed while traffic is groomed as efficiently as possible in the unidirectional IP links and the bidirectional optical line-systems. The goal of this second case study is thus to study how the cost increase caused by

the unidirectional IP traffic demand can be tempered by using our efficient multi-layer grooming algorithm FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$. In order to assess its performance, it is compared with the methodology applied in Reference [17]: SP \rightarrow SP.

5.2.1. Network under study. For this second case study, we use again the test network of Subsection 5.1.1, but with a slightly different traffic running over it. We then let the IP traffic demand asymmetry factor (AF) vary between 0 and 75%, according to the methodology discussed in Reference [17]:

$$\text{Asymmetry factor IP traffic demand} = \frac{\sum_{i,j,i \neq j} |M_{ij} - M_{ji}|}{\sum_{i,j,i \neq j} |M_{ij} + M_{ji}|}$$

where M_{ij} is the IP traffic demand from node i to node j .

In order to see the effect of increasing traffic volume, we have done this for the forecasted IP traffic demand in the time frame 2002–2008 (see Figure 11). The same cost model as the one discussed in the first case study was used.

5.2.2. Influence of IP traffic asymmetry. Figure 12 shows the cost evolution for increasing traffic asymmetry and increasing traffic volume for two of the above studied multi-layer traffic grooming algorithms: SP \rightarrow SP and for FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$. Figure 12 clearly shows that using the FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$ algorithm results in significantly lowering the overall network design cost than in the case SP \rightarrow SP is used, and this for the four considered IP traffic AFs (0, 25, 50 and 70%).

In Figure 13, the cost difference between SP \rightarrow SP and FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$ is shown again.

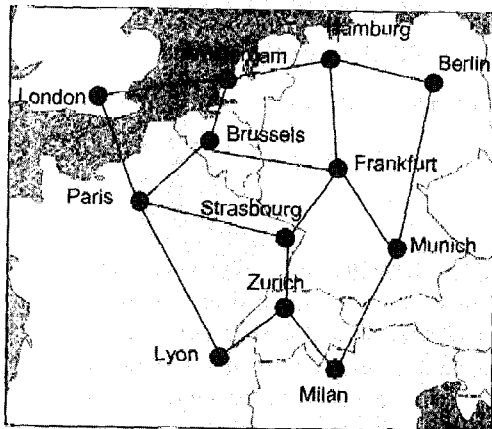


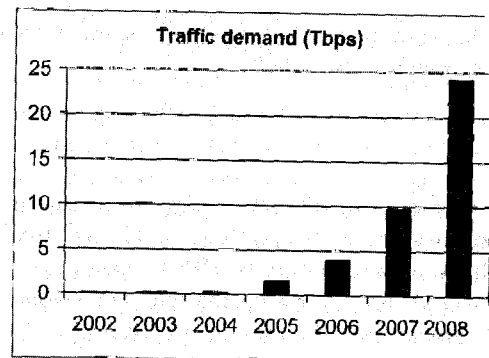
Figure 11. European candidate physical topology and forecasted traffic for 2002–2008.

These figures clearly illustrate the increased cost-efficiency of the FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$ multi-layer traffic grooming algorithm compared to SP \rightarrow SP in dealing with asymmetric traffic demands. For all four considered IP traffic AFs (0, 25, 50 and 70%) and for the whole considered time range (2002–2008), the overall network cost obtained with FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$ is lower than that obtained with SP \rightarrow SP.

6. CONCLUSION

In this paper, we have described several multi-layer traffic grooming algorithms for an IP/MPLS-over-optical network scenario. Where most of the research on traffic grooming has been focusing on ring networks, we have assumed the optical layer to have a meshed topology. This is appropriate as in today's backbone networks the transition is being made from networks arranged in rings to networks arranged in a general mesh topology, due to, for example the growth of IP data traffic. The algorithms also take into account the inherent asymmetric nature of the traffic offered to the IP/MPLS layer (mainly due to the IP traffic).

The obtained results demonstrate the efficiency of our proposed multi-layer traffic grooming algorithm which uses the efficient forward synthesis and design tightening algorithm to solve the minimum cost capacity installation problem in both the IP/MPLS layer and the optical layer, and deploys a charging-based feedback loop. Compared to the other described algorithms, a serious cost saving in the overall network cost can be achieved. The influence of deploying the efficient FS + DT heuristic, the influence



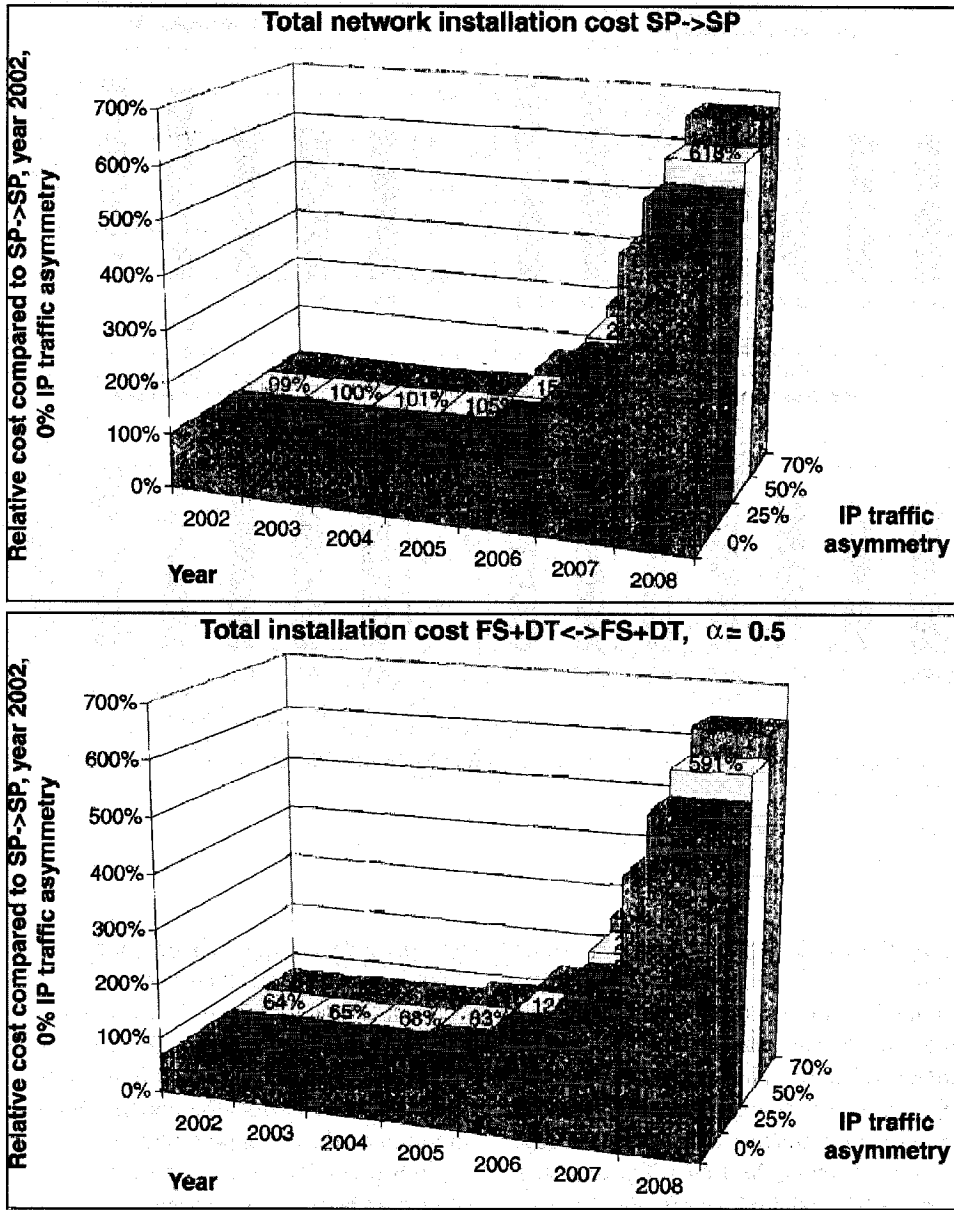


Figure 12. Cost evolution for increasing traffic asymmetry and increasing traffic volume for SP → SP and for FS – DT ↔ FS + DT, $\alpha = 0.5$.

of using a feedback loop and the possibility to fine-tune this feedback loop implementation have all been discussed in detail. It was shown that our algorithm also allowed for a more gradual installation of capacity in the network, in that way spreading the network installation cost. Finally, the efficiency of this multi-layer traffic grooming algorithm under various asymmetric traffic conditions was highlighted.

APPENDIX A: FS – DT ALGORITHM

A solution to the minimum cost capacity installation problem in a single-layer network can be found by applying the FS + DT heuristic algorithm. The flowcharts of this algorithm are depicted in Figure 14.

In the first stage of this two-stage algorithm, the network is dimensioned to carry all the traffic demands. Hereto

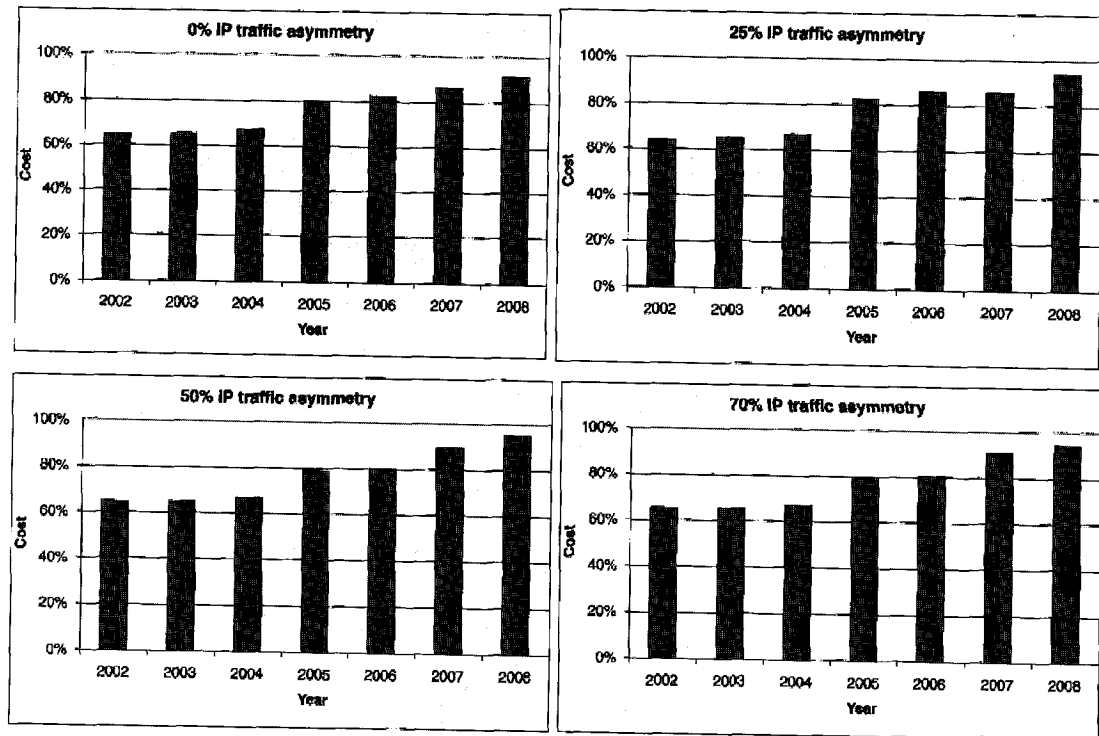


Figure 13. Relative cost of FS + DT \leftrightarrow FS + DT, $\alpha = 0.5$ compared to SP \rightarrow SP (100%) for various asymmetry factors of the traffic and for increasing traffic volume.

each commodity of the traffic demand matrix is routed along its cheapest path on the network. This allows determining the total flow on each link (bidirectional) or arc (unidirectional), and through each node in the network. Capacity on the IP or optical links and in the IP routers and OXCs is however installed in discrete amounts. Installing another line-system on an optical link increases the capacity of that link with, for example 40 10 Gbps channels. Typical OXC sizes are 64×64 , 256×256 , etc. The same applies to IP routers. The total flow on each link or arc and through each node is then rounded down, such that it completely fills up a wavelength (in the IP layer), a line-system (in the optical layer) and all ports of an IP router or OXC. If the flow on a link or arc or through a node is too small to fill up a complete facility, no line-system or node equipment is installed. In a next step, an attempt to solve the multi-commodity flow (MCF) problem is made. In most cases, the MCF problem cannot be solved with the line and node facilities installed in the network at that point. The algorithm will then search for the line or node facility that has the largest excess traffic per unit cost and an extra

line or node facility will be added to this link or node. Another attempt will then be made to solve the MCF problem. Extra facilities will be installed in the network until the MCF problem can be solved. The network is now dimensioned to carry the traffic demand.

In the second stage, the results obtained in the FS stage are improved by dropping underused facilities and rerouting this part of the traffic. Starting from the solution found after the FS stage, the redundant capacity cost of the links and nodes in the network is calculated. The redundant capacity of a link or node is the portion of the installed link or node capacity that carries no traffic in the current routing. The redundant capacity cost is then the redundant capacity multiplied with the cost per capacity unit for installing a facility on this line or node. The nodes and links are then ranked in a list sorted in order of decreasing redundant capacity cost. As long as the list is not empty and not all elements in the list have been considered, a facility is removed on the next element in the list. If the MCF problem cannot be solved with this reduced number of facilities, the facility is again added to the network and

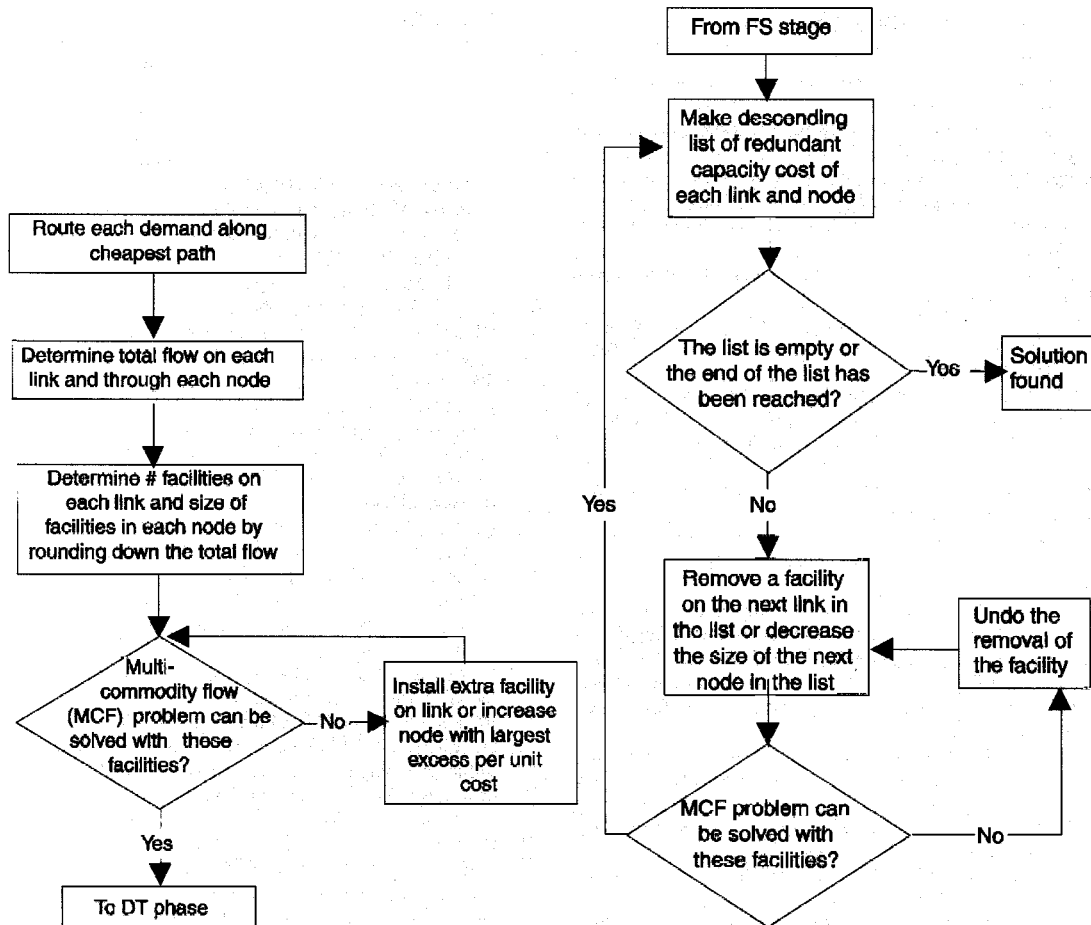


Figure 14. Forward synthesis (FS) stage (left) and design tightening (DT) stage (right) of the two-stage MCCI problem.

the next element in the list is considered. If the MCF problem can be solved, a new descending list of the redundant capacity cost of the links and nodes is drawn up. This is repeated until the list is empty, or all elements of the list have been considered.

This FS + DT algorithm is based on the one described in Reference [26]. However, in Reference [26] only line costs were considered (the algorithm only allowed for the installation of line-systems). In the above-explained algorithm both link and node costs have been taken into account, as was explained in Subsection 5.1.2. Therefore each node n_i in the network was replaced by two nodes IN_{n_i} and OUT_{n_i} , interconnected by a unidirectional link $IN_{n_i}-OUT_{n_i}$ from IN_{n_i} to OUT_{n_i} . The bidirectional optical links n_i-n_j in the network are replaced by two coupled unidirectional links $OUT_{n_i}-IN_{n_j}$ and $OUT_{n_j}-IN_{n_i}$. As these links are coupled, the same amount of capacity (optical line-systems) will be installed on these unidirectional

links. If the network was a unidirectional IP/MPLS network, both links are not coupled, as the links in an IP/MPLS network are assumed to be unidirectional. Applying the link-based FS + DT algorithm explained in Reference [26] on such a modified network leads to the FS + DT algorithm explained in Figure 14, and used in this paper.

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