Periodic reconfiguration of groomed multicast trees in WDM networks

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In a typical multicast scenario the tree members (users attached to the tree) change all the time. New users join the tree, while some existing users leave it. Here we consider these dynamically changing multicast trees in two-layer, grooming-capable, optical networks. The continuous changing of the tree members (users) causes the degradation of the tree. Therefore a huge amount of network resources can be spared by periodically repeated reconfiguration. In this paper the benefits of reconfiguration are investigated for different multi-cast routing algorithms and reconfiguration periods.

1. Introduction

In recent years the traffic due to multipoint network-based applications keeps on growing in transport networks. Multipoint applications include very important broadband services such as digital media broadcasting (e.g. IP-TV, IP-Radio, etc.), VoD streaming, distance learning, virtual private LAN services, etc [1].

In spite of its benefits in terms of bandwidth savings, today the multicast service is not made available to the end users by most commercial ISPs due to a number of practical reasons. This means that today a huge amount of bandwidth is wasted due to multipoint delivery based on application-layer multicasting (ALM) i.e. unicast-based distribution. In this sense, a recent application that may impel the operators to open the multicast service is TV peer-casting. This application is starting to take an unnecessarily high share of the network capacity as the same streaming information comes in and out of the network for thousands of users by unicast relaying.

Nonetheless, even though not directly available to end users, the multicast service is an essential feature present in the core of the transport network because it is the key to the scalable implementation of the triple-play concept: TV channels are usually multicast from a content distributor to local caches/relays near the end users.

In general, it can be said that it is less costly to implement multicast in the lowest layers of the network hierarchy; however, when the underlying technology is connection-oriented – as it is the case of optical networks – the number of supported connections becomes a strict bound. In the case of wavelength-routed optical networks, this limit is set by: the number of lambdas, the amount of multipoint units in optical nodes, their fan-out and the optical power budget. Given this limitation, optimizing light tree construction is quite a relevant challenge in next generation multicast-capable optical networks.

In this paper we investigate the problem of dynamic multicast trees, where the member tree leaves are continually changing. New destination nodes may log in to the tree to receive the content, while other nodes may leave the tree and return at a later time. This corresponds to a scenario where IP membership drives optical tree set up. In a real setting, the tree would be “optical” due to the aggregation of multiple multicast sessions or it could be given by a selected set of individual ultra broadband multicast sessions. Several multicast trees can exist in the network at the same time. If the trees have sub-lambda bandwidths, grooming can be applied to make network utilization more efficient.

A typical application can be a digital media distribution service, where the audience is varying in time. New customers appear, who subscribe for the content, and other customers with expired subscription leave the network. In this case a customer does not necessarily mean an individual home user, rather a local provider (e.g. a local cable-TV provider).

Another example can be a virtual LAN service, where LAN broadcast has to be delivered to all endpoints. In contrast to the previous scenario, this application is less sensitive to minor interruptions in transmission caused by reconfiguration of the multicast tree.

The continuous changing of tree members causes the degradation of the multicast tree in the sense of network and resource costs. This degradation can be cured by regular reconfiguration of the tree. Reconfiguration results in significant spare of network resources (and of the cost), which is clearly beneficial for the operator: resources (including link capacities) that are freed up can be reused.

However, there are also some drawbacks of reconfiguration:

It may consume lots of computation time as computing the Steiner tree is an NP-complete problem. However, considerable saving can be achieved by using faster heuristic methods trading-off speed and optimality.

Reconfiguration can cause a short disruption in the data transmission flow or cause packet reordering, which is sometimes not acceptable by the application and should be avoided. Furthermore, reconfiguration implies an additional signaling overhead.

1.1. Surviving to tree reconfiguration

Although our paper does not intend to solve this problem, we suggest some techniques to show that it is feasible.

A solution for an interruption-sensitive application (e.g. media streaming) is a soft switch-over from one light tree to the new one. In this case the updated light tree is already set up, before the old one is torn down. There is a short period when both trees exist and are able to transmit data at the same time. In order to prevent loss of sequence during the change of the tree, the transmission can be held for a short time at the ingress to guarantee that all the packets are flushed out of the original tree. Alternatively, the first packets that travel through the new tree are buffered at the egress node until an end-of-transmission signaling packet arrives through the old tree. However, smooth reconfiguration needs extra resources from the network. In our simple network model if one free wavelength is available in every link the reconfiguration of one light-tree can be performed – for example by *ILP* (Integer Linear Programming) optimization. In a DWDM network with at least 30 WLs per link this extra capacity is acceptable (especially compared to the huge cost gain, that the optimization results). However, it is not guaranteed that this extra capacity is always available.

1.2. Other publications in the area

Quite a few papers were published in the field of optimizing the cost of multicast routing (light-trees) in optical networks. Since the problem of routing the demands optimally is often infeasible or time-consuming, several heuristic approaches were proposed and their performance was compared with ILP-based optimal solutions.

The problem of static multicast for optical wavelength routing was investigated for ring and mesh networks among others in [2] and [3], respectively. The authors of [3] presented an analytical model of grooming problem represented as non-linear programming formulation and compared the results with heuristic approaches. Heuristic optimization algorithms are proposed in [4-6]. The authors of [7] use an ILP formulation to solve the optimal routing and wavelength assignment problem, and show that a network with only a few splitters and wavelength converters can efficiently transfer multicast demands. Mustafa et al. [8] also presented an ILP formulation and heuristic solutions assuming grooming for minimizing the number of electronic-layer equipments and the number of wavelengths.

In recent time the optimization of dynamically changing multicast trees attracted more attention. In the dynamic case the goal is usually to minimize the blocking ratio, not to route all demands (according to some constraints) as in the static case. This problem in general is even more resource- and computation-intensive than the static version. We found, however, that some subproblems of routing (e.g. optimization of a single tree, or several trees separately) can be solved optimally by ILP. Therefore, it is worth to compare the performance of dynamic routing algorithms to the optimal solution, and to calculate the benefit.

Several provisioning methods of dynamic trees (assuming grooming) are discussed in [9-11].

In [12] traffic engineering is performed through dynamic traffic grooming in grooming-capable WDM networks in the unicast scenario.

The authors of [13] proposed a dynamic wavelength assignment algorithm for multicast to minimize call blocking probability by maximizing the remaining network capacity in each step. Chowdhary et al. addressed in [14] a similar problem by provisioning on-line multicast demands with the objective of increasing the resource utilization and minimizing the blocking probability for the future arriving requests.

Boworntummarat et al. introduced light-tree-based protection schemes against single link failure in [15]. ILP formulations were developed to measure and compare the minimum spare capacity requirement of the proposed protection strategies.

According to our knowledge no work was published analyzing the effect of regular reconfiguration of light-trees, investigating the degradation of dynamic routing algorithms, and comparing the dynamically changing costs to the optimum.

2. Problem formulation

A two-layer network is assumed, where the upper, electronic layer is time switching capable while the lower, optical layer is a wavelength (space) switching capable one. The electronic layer can perform traffic grooming, i.e. multiplexing low bandwidth demands into a single WL channel. The two layers are assumed to be either interconnected according to the peer model [16] or vertically integrated, i.e. the control plane has information on both layers and both layers take part in accommodating a demand.

The network topology and the number of fibers are assumed given as well as the parameters (distribution of inter-arrival time and holding time) of dynamic traffic demands. The capacity of WL channels and the cost of routing, (e.g. space switching, optical to electronic conversion, etc.) can also be given in advance.

We assume dynamic traffic consisting of multicast traffic demands. As explained before, these demands may correspond to an individual ultra-high speed IP multicast session or to a set of aggregated sessions that share most of the leaves. The heuristics for aggregating multiple sessions into a single light tree fall out of the scope of this paper. The same consideration is made regarding joint optimization of light trees and light tree merging: for the sake of simplicity, in this paper light-trees are optimized separately, although, joint optimization could yield a higher cost gain at a higher computational cost.

A multicast tree consists of multiple so-called sub-demands, which can share resources in the network (e.g. their bandwidths are not additional). One sub-demand is assigned to each destination node (member) of the tree. The source of every sub-demand is the single source node of the multicast tree. Destination nodes of the tree change dynamically: new nodes can log in the tree or existing nodes can log out at any time. Paths of new sub-demands have to be calculated online while paths of leaving nodes need to be torn down as carefully as possible not to affect other sub-demands.

Both the active session time (holding time) and the idle (inter-arrival) time for every destination node have an exponential distribution. The traffic load can be determined by appropriately setting the rate parameters (λ) of the distributions. The objective is to reach all current destination nodes from the source in each time step.

3. Network model

We use a wavelength graph model for routing in two layer networks with grooming and with different types of nodes. The model handles any regular mesh topology and supports the peer-model. The WL graph that corresponds to the logical network is derived from the physical network considering the topology and capabilities of physical devices.

A simpler version of the model has been first proposed in [17]. ILP formulation of the static RWA problem with grooming and protection has been given in [18].

The network consists of nodes and links connecting the nodes. Both ends of an optical link (fiber) are attached to an interface (IF) of a physical device, which determines the number of supported WLs in the fiber. Every physical device contains an internal switching fabric and some IFs. Each link and every physical device has a specific logical representation in the WL graph.

A physical link is derived to as many logical edges as the number of available WLs in the link. The logical sub-graph of a physical device depends on the capabilities of the device. Every edge in the graph has a capacity and a cost of usage. The capacity of the edge usually equals to the WL capacity, which depends on the used carrier (typically 2.5 Gbps – which was assumed in our simulations – or 10 Gbps). The cost of the edge is determined by its functionality (WL edge, O/E conversion, etc.).

The WL graph model (together with our ILP framework) can support devices with different capabilities appearing in the network at the same time. The model is easily extendable; the type of devices can be changed later if new internal models are introduced.

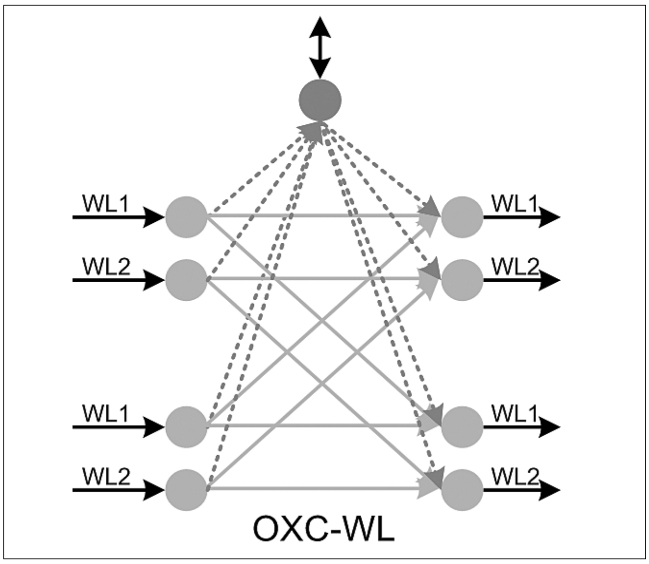


Figure 1.
Sub-graph of an OXC-WL device in the wavelength graph

A sub-graph of a versatile physical device is depicted in *Fig. 1.* The equipment is a combination of an OXC with WL-conversion and an OADM that can originate and terminate traffic demands, as well as perform space switching. WL-conversion and splitting (branching) of light-trees can only be performed in the electronic layer. We will use this complex node in our simulations.

4. Routing algorithms

We applied several algorithms to route the demands in the network. We wanted to compare their costs and performances. A simple example illustrating the different outcome of the algorithms is shown in *Fig. 2.*

4.1. ILP routing and formulation

ILP always provides the optimal cost of routing the current demands in the system, thus it serves as a baseline for comparison. However, this does not necessarily mean that the numbers of certain resources (e.g. wavelengths, O/E, E/O converter ports) are all minimal as well. On the other hand ILP routing usually consumes much time. Fortunately, the routing time of one multicast tree is still acceptable even for larger networks. This time varied from 3 seconds to 180 seconds on a 2.8 GHz Pentium for COST266 network [19], which consists of 28 nodes and 41 links. If we want to route several trees together by introducing grooming much more cost can be spared, however, the solution time becomes unacceptably high. So it is only possible to route different trees separately one after the other.

An important disadvantage of ILP routing is that the consecutive configurations are very dissimilar, thus reconfiguration of the paths of demands (including switching devices along the path) is unavoidable.

We used the ILP formulation introduced in [22] and [23] to route multiple multicast trees in the network.

This formulation is able to route unicast and multicast demands as well, or even demands from both types at the same time.

4.2. Accumulative shortest path (Dijsktra's algorithm)

Accumulative shortest path algorithm is fast and simple. It can be applied for routing a new demand by not interrupting the current active sub-demands in the network. On the other hand this algorithm is rather costly.

The accumulative shortest path algorithm works as follows: routes are calculated between the source and the destination nodes one after the other. The algorithm operates directly on the logical network (wavelength graph). The source and the destination nodes of a sub-demand are the electronic nodes of the corresponding physical device. The cost of already reserved edges of the graph is set to zero, which means it can be used for free.

Paths to leaving destination nodes are cleared. Edges that are not used by the multicast tree anymore are de-allocated (i.e. this sub-demand was the last one that used these edges). Dijsktra's algorithm never modifies paths of existing sub-demands, which unfortunately often results in longer paths.

4.3. Minimal Path Heuristic (MPH)

The MPH algorithm transforms the original wavelength graph into a virtual graph and applies Prim's algorithm [20] to form a minimum cost spanning tree. A virtual graph is a full mesh, in which only the single source and all the destination electronic nodes are presented. The weight of an edge in the virtual graph expresses the cost of the shortest path in the original wavelength graph (which implies that the shortest path has to be calculated for every node pair in back and forth).

Prim's algorithm is applied in this "upper-layer" virtual graph. After the minimal cost spanning tree is found the paths are traced back into the original wavelength graph. Already used edges of the virtual graph are equal to zero when updating the spanning tree after a new destination node logs in. This ensures that paths of existing sub-demands are not modified. Details of MPH algorithm can be found in [21].

4.4. Tree routing

This algorithm is similar to the MPH algorithm, except that it operates in the wavelength-graph, not in a derived "upper layer", virtual graph. It applies the same Prim's algorithm to determine a minimal cost spanning tree in the WL graph. Updating the tree and modification of the edge costs are also similar to the former case.

A phenomenon can occur in case of both, tree routing and MPH that needs attention: trees can branch in such nodes, where splitting is not allowed (i.e. in non-electronic nodes). These forbidden branches need to be corrected by a post-processing. In fact it is pretty simple to solve the problem by moving both branched paths up to the electronic layer.

5. Results

The simulations were carried out on the COST 266 European reference network [26] with the same traffic demands used in case of all algorithms.

In *Fig. 3.* the cost of routing is plotted as a function of elapsed events. Every change of the light-tree (i.e. a destination node enters or exits the tree) is considered as an "event". In Fig. 3 the lower curve marked as ILP represents the optimal cost in every step, while the upper one (marked as Dijkstra with no reconfiguration) stands for the case when no reconfiguration was applied. The middle curve shows the effect of the regular reconfiguration in every 20th event.

In our experiment "Dijsktra without reconfiguration" exceeds the optimal solution by more than 60 percent

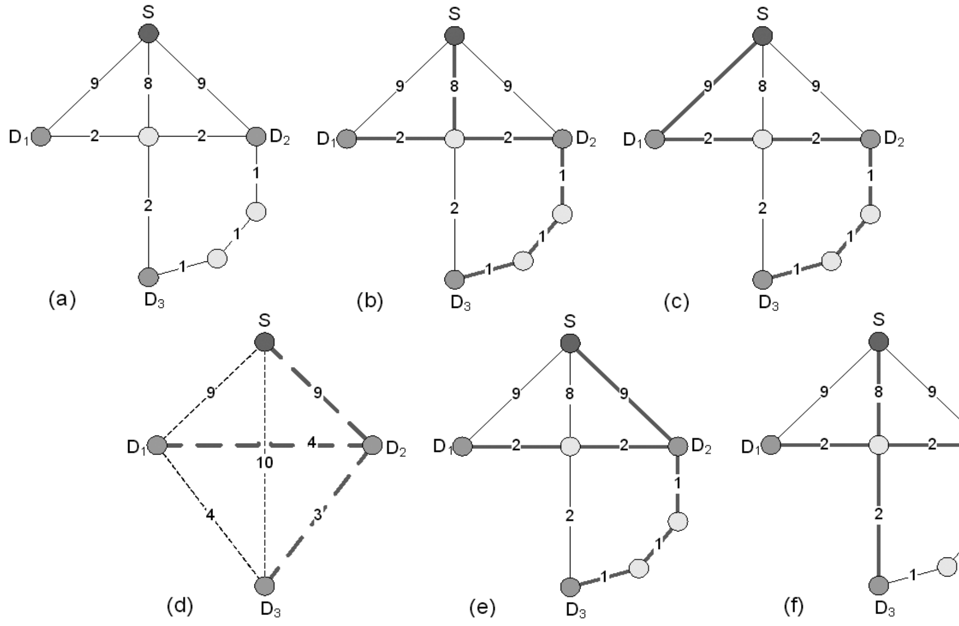


Figure 2.
(a) Original topology with the source node S and three leave nodes D1, D2 and D3,
(b) tree routing,
(c) accumulative shortest path routing,
(d) MPH virtual topology and routing,
(e) MPH routing,
(f) ILP optimal routing

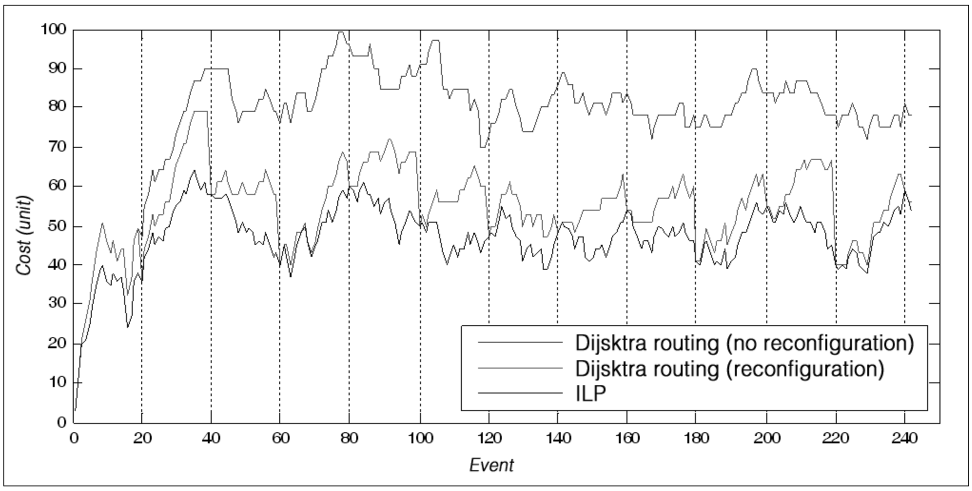
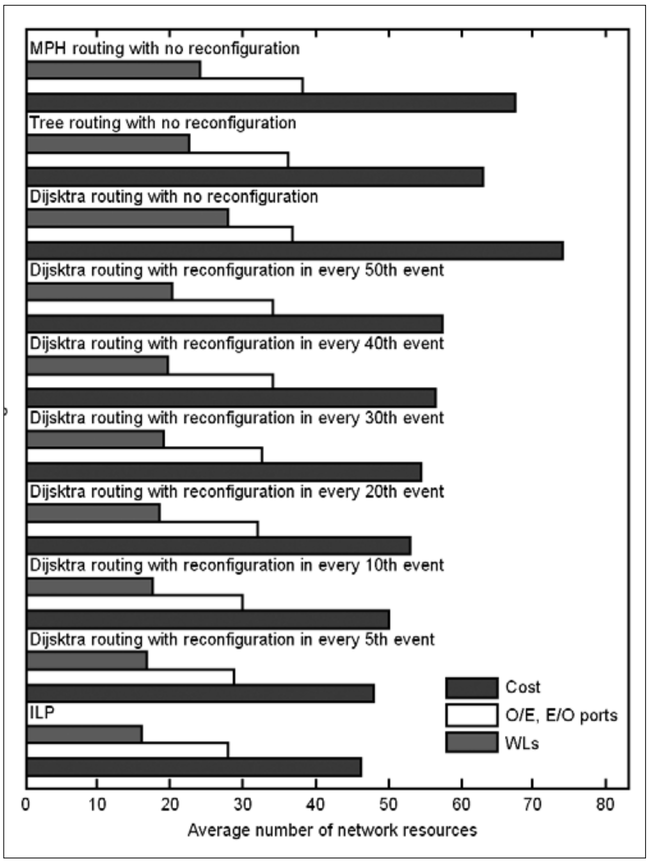


Figure 3.
The cost of routing as a function of elapsed events for Dijsktra's algorithm with (middle curve) and without (upper curve) reconfiguration compared with optimal ILP solution (lower curve)

on average. The reconfiguration curve usually diverges rapidly from the optimal curve. It has the same cost, though, as the optimal one in every 20th event because of the reconfiguration. Although reconfiguration is clearly beneficial (according to Fig. 3), it surely depends on the network topology, the applied dynamic routing algorithm and the reconfiguration period as well.

Therefore we also investigated the cost of different routing algorithms (described in Section 4), and accumulative shortest path routing (Dijsktra) with different reconfiguration periods.

Figure 4.
The average routing cost, conversion ports (O/E, E/O) usage and WL usage of different algorithms and (Dijsktra's) shortest path algorithm with different reconfiguration periods

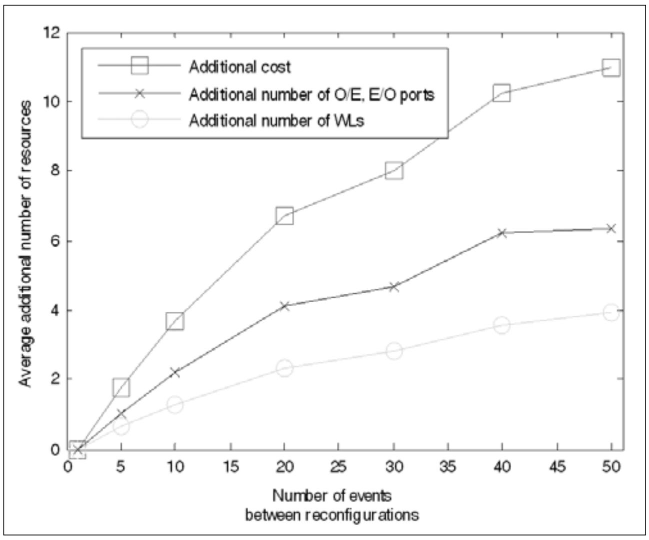


The results are depicted in *Fig. 4.* It is clear, that all of the algorithms (without reconfiguration) are far from optimal: in the current simulation the additional cost is around 34 to 57 percent compared to the optimum. Much cost can be spared by regular reconfiguration. As expected, the shorter the period of reconfiguration, the closer the average cost approaches the optimal value. However, we should know that reconfiguration can be computation-demanding and has other disadvantages as well (see Section 1.1). These drawbacks are not taken into account in the cost.

The results are very similar for network resources necessary to realize the routing: i.e. the number of required O/E and E/O conversion units and the number of wavelengths (Fig. 4).

One interesting fact is that Dijsktra's algorithm without reconfiguration has an outstanding WL usage, while the usage of opto-electronic converters is behind MPH routing. Both WL and conversion port usage approach optimal value by decreasing the length of reconfiguration period.

Figure 5.
The average additional cost of routing (upper curve), number of O/E, E/O conversion ports (middle curve) and number of WLs (lower curve) as a function of the length of reconfiguration period



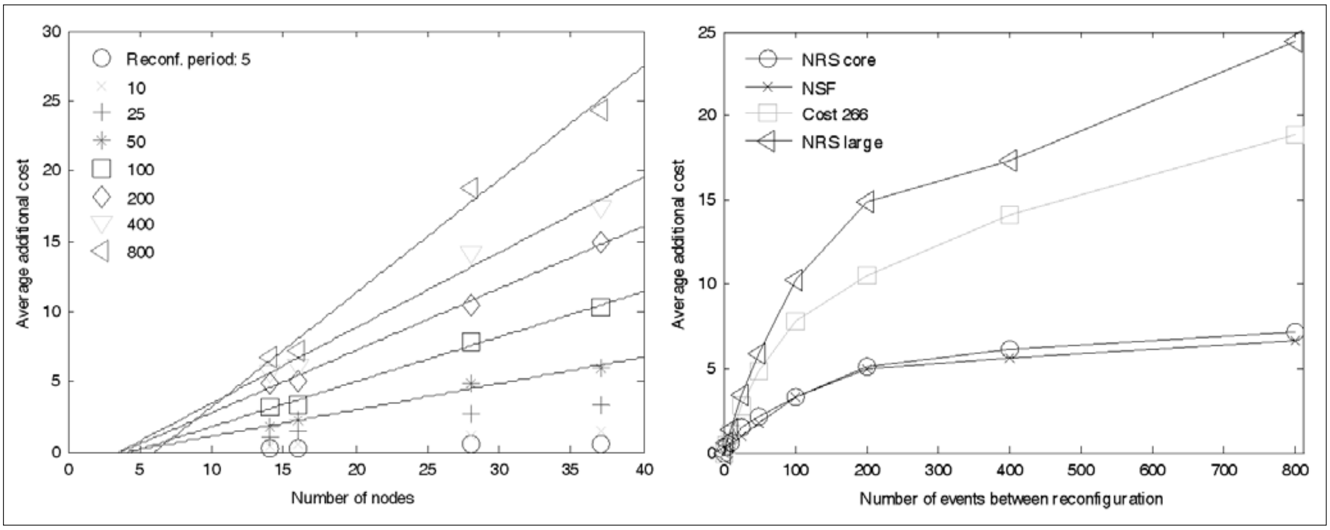
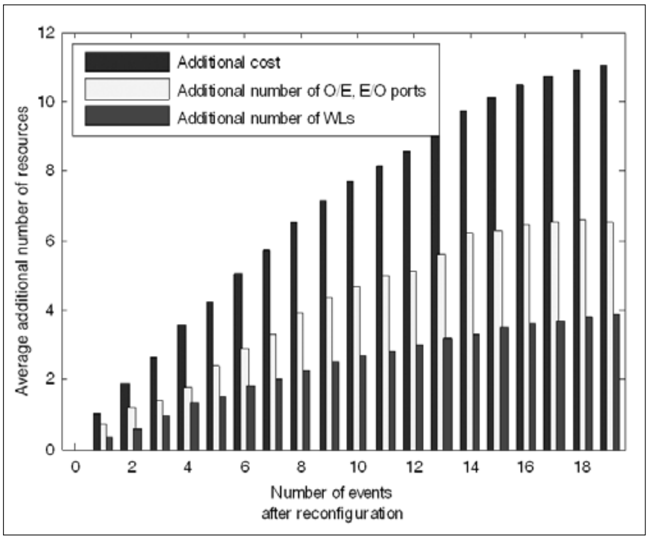


Figure 6.
The average additional cost for different network topologies (left),
and the average additional cost as a function of the number of nodes in the network (right)

We also wanted to investigate how the length of the reconfiguration period affects the cost gain. The average additional cost of routing as a function of the length of reconfiguration period is depicted in *Fig. 5.* The figure shows a saturating curve with decreasing slope. This means, that if we want to reach high cost gain, frequent reconfiguration is necessary. There is not much difference between cost gains, when the periods are long. The required number of WLs and conversion ports follow the same rule, both have a decreasing slope.

We repeated the same measurement for several reference networks to study how the additional cost curve (as a function of the reconfiguration period) looks like in case of different topologies. The same amount of traffic was injected in all of the networks. We obtained similar saturating curves again for all topologies (see *Fig. 6., left).*

Figure 7.
The average additional cost of routing (higher bar),
number of O/E, E/O conversion ports (middle bar)
and number of WLs (lower bar)
after reconfiguration as a function of elapsed events



However the slopes of the curves differ. For larger networks the additional cost rises more rapidly as the length of the reconfiguration period is increased. Therefore we depicted the additional cost as a function of the number of nodes in the network *(Fig. 6, right).* The symbols mean different lengths of reconfiguration periods; the linear regression was also computed for most of the data series to show the clear linear trend. We found similar relationship between the average additional cost and the number of links in the network. However, the trend is not obviously linear in that case.

Topology	**Number of nodes**	**Number of links**
NRS core [24]	16	23
NSF net [25]	14	21
Cost 266 [26]	28	41
NRS large [24]	37	57

Table 1. Reference networks used in the simulations

Based on this experiment it can be assumed that the additional cost is proportional (as expected) to the number of nodes and to the number of links in the network, which means that the larger the network is, the more frequent reconfiguration is required.

Fig. 7. shows how fast the cost of the optimized reconfigured light-tree diverges from the optimal curve. This one is also a saturating curve with decreasing slope, similar to the left one. This suggests that in the first few steps the cost of the tree quickly diverges from the optimal curve, then during the next few events this divergence is slowing down. This kind of divergence is true in terms of conversion ports and WLs as well: after reconfiguration the multicast tree quickly uses more network resources compared to the optimal topology.

The next figure *(Fig. 8)* displays the cost of routing as a function of the number of destination nodes of the light-tree. Each data point corresponds to one time-step in the simulation. The figure compares shortest path rout-

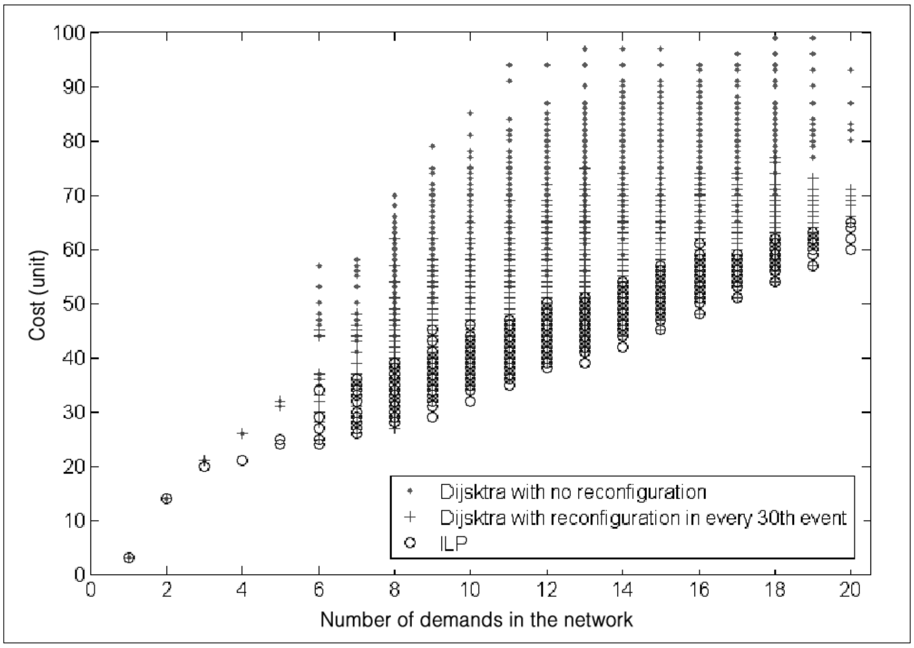


Figure 8.
The cost of routing as a function of the number of destination nodes of the light-tree

ing with and without reconfiguration to the optimal solution. As expected, the routing cost naturally raises as the number of the destinations increases. The signs show the typical ranges of the dynamically changing cost for the routing methods. It is noticeable that the range of shortest path with reconfiguration is somewhere between the optimum- and the “no-reconfiguration” range.

In our last experiment we are considering multiple trees (5) at the same time with specific bandwidths. Note, that in this case all trees were optimized separately by ILP in a certain order (in decreasing order of tree size), which does not provide the global optimum. These bandwidths are set so that grooming should be applicable. The routing cost (including conversion port and WL usage) of shortest path routing and ILP are compared. The figures suggest that reconfiguration is more beneficial in case of higher bandwidths, since grooming is less useful in such a case. This observation is true for both the necessary number of conversion ports and WLs, and for the total cost as well *(Fig. 9-11)*.

6. Conclusion

In this paper we showed that reconfiguration of dynamic light-trees is clearly beneficial for the transport network operator. Lots of cost (including network resources, e.g. O/E converter units and wavelength capacity) can be spared by restoring the optimal topology of the tree. Since after the reconfiguration the tree diverges quite quickly from the optimal one frequent reconfiguration is required.

In this paper we have tried to measure the cost saving and the dynamics for periodic reconfiguration with several heuristics. The results show that reconfiguration can be a cost-effective option if the average time between events (subscriptions or leaves) is enough to take advantage of the WLs saving achieved. In this case the saved resources make up for the reconfiguration cost. Still, a number of technical challenges must be addressed to make reconfiguration practical, like the seamless switch over of traffic from the old to the new tree.

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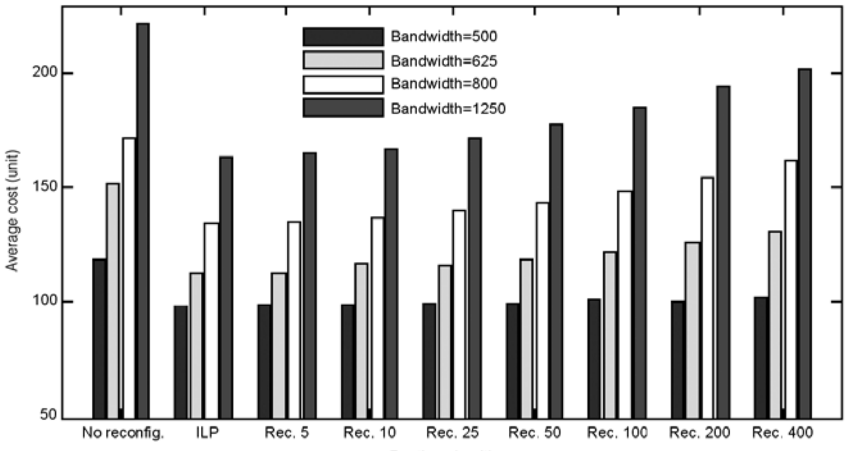

Figure 9.
Average routing cost
for different bandwidth of demands

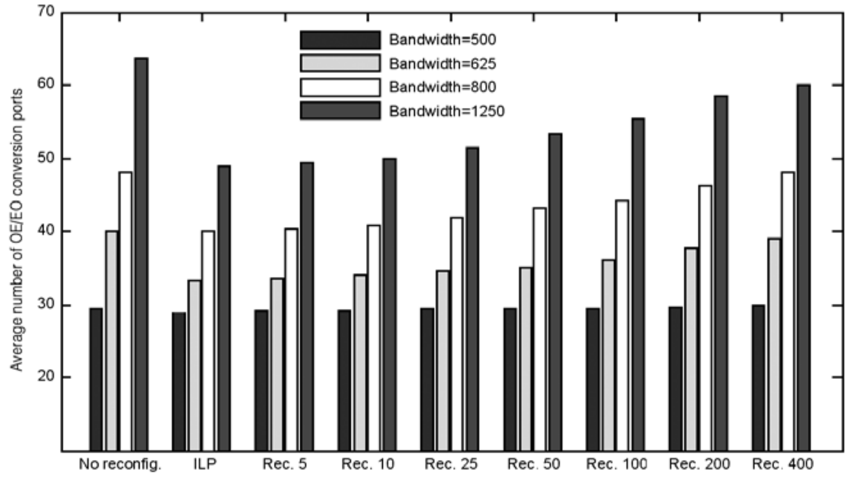

Figure 10.
Average number of
converter ports (O/E, E/O)
for different bandwidth of demands

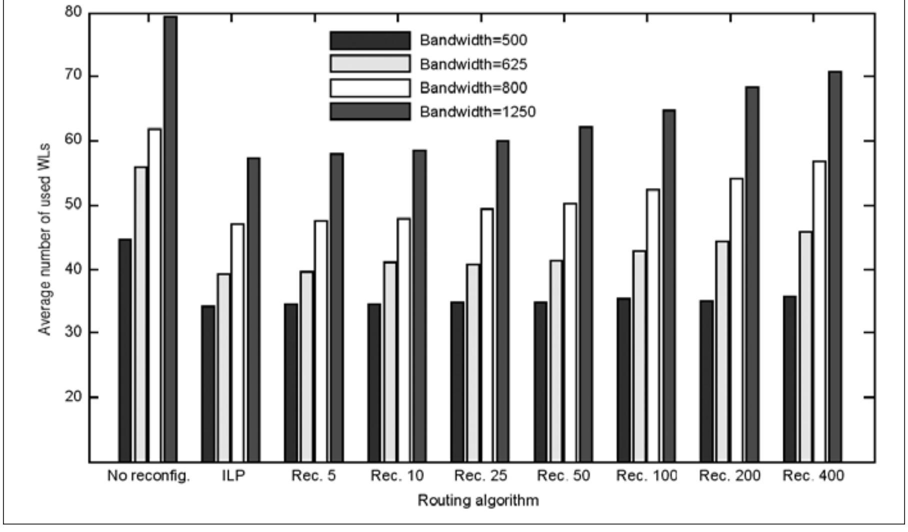

Figure 11.
Average number of used WLs
for different bandwidth of demands

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