Comparison of SDH/SONET-WDM Multi-Layer Networks with Static and Dynamic Optical Plane

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Abstract—SDH/SONET-WDM multi-layer networks are a very attractive solution to cope with the increasing dynamics and capacities in todays core networks. In SDH/SONET multi-layer networks, client layer SDH/SONET connections are groomed to wavelength channels and transported using end-to-end lightpaths. Also, intermediate grooming can yield to a more efficient utilization of network resources.

In this paper, two principal SDH/SONET-WDM multi-layer network architectures are investigated covering the dynamics either only in the electrical layer or in both layers, respectively. In order to show benefits and drawbacks for the introduction of dynamics in the optical plane of todays backbone networks, we present a detailed performance evaluation based on simulation studies and compare both architectures for different total network capacities and grooming strategies. We also systematically analyze the traffic composition which until now has only rarely been investigated. We show that changes in the traffic pattern can be covered by a dynamic optical plane. Further, we figure out the timescale for switching operations in the optical layer which is at least two orders of magnitude below the connection's interarrival rate.

Index Terms—Photonic Networks, Multi-Layer Traffic Engineering, Performance Evaluation, Simulation

1. Introduction

The increasing usage of the Internet around the world has been leading to a massive growth in traffic volume and dynamics to be transported by network backbone. To cope with this, highly flexible and dynamic IP-over-WDM solutions were envisioned a few years ago that provide virtually unlimited bandwidth and support dynamics not only in the electrical layer but also in the optical layer. During the dot-com-bubble, the need for circuit-switched connections of smaller bandwidth than full wavelengths was mostly neglected and greenfield solutions with large optical cross connects seemed close to reality. However, today carriers look much more closely at new business opportunities as well as operating and capital expenditure (OPEX/CAPEX) reductions and thus an important requirement is the bandwidth provisioning at sub-wavelength granularity.

On the one hand, standardization bodies have recently defined and researchers investigated dynamic network architectures like automatic switched transport networks (ASTN [19]), automatic switched optical networks (ASON [22]) or generalized multiprotocol label switching (GMPLS [1]), that all allow for a flexible dynamic adaptation of the network to changing demands using an intelligent control plane.

Explicitly these approaches consider circuit switched networks like SDH/SONET at the same time yielding *Next Generation SDH*: Generic framing procedure (GFP [20]) and link capacity adjustment scheme (LCAS [21]) extend the flexibility of SDH/SONET such that data services can be efficiently transported and the dynamic adaptation of bandwidth is possible which both will allow for new services. Also, virtual concatenation (VCAT [18]) allows to select the connection bandwidth in integer multiples of VC-11/12/2/3/4. For example Gigabit-Ethernet (GbE) can be mapped into a VC-4-7v connection with an efficiency of 95% instead of 40% efficiency when using an STM 16/OC 48 connection. On the other hand, network architectures that highly rely on statistical multiplexing in the optical layer like optical burst switching (OBS) and optical packet switching (OPS) have been investigated during the last few years. While they can inherently cover the high dynamics of Internet traffic there is no direct migration path from todays static SDH/SONET networks based on point-to-point WDM links to IP-over-OBS/OPS as these approaches require a installation of a completely new switching and transmission infrastructure.

One feasible solution within the context of ASTN/ASON is an enhanced automatically switched SDH/SONET-WDM multi-layer network that provide dynamics on both layers in order to cover the dynamics of IP traffic as well as to provide bandwidth adaptable connections. SDH/SONET-WDM multi-layer networks consist of multi-layer nodes with cross connects on the SDH/SONET layer as well as on the WDM layer. A main reason for this approach is the fact that a clear and efficient evolution path for the large base of installed SDH/SONET networks exists. Although the network investigated in the following is based on an electronic SDH/SONET layer, an MPLS layer instead will yield the same principal results as an SDH/SONET connection and an MPLS path with a certain reserved bandwidth are modelled very similarly here. Also, as the SDH and SONET are corresponding International Telecommunication Union (ITU) and American National Standards Institute (ANSI) standards we will use only SDH in the following.

In this paper we compare in a detailed performance evaluation two basic multi-layer node architectures with respect to the traffic composition and network capacities. Furthermore, we show that a stepwise introduction of this kind of networks is possible in the course of the change of traffic patterns in backbone networks as well as type of services. In [2], Bodamer et al. investigate comparable architectures and show basic results for one network scenario. We focus in this paper on a detailed analysis of the impact of network and traffic characteristics.

The remainder of this paper is structured as follows: in Section 2 the investigated network and node architectures are introduced. Principal basic grooming and routing schemes for these networks are presented and discussed in Section 3. In Section 4, the behavior of those schemes in the different network scenarios is investigated through simulations. Finally, conclusions are formulated in Section 5.

2. Multi-Layer Network and Node Architectures

Current static point-to-point SDH networks comprise nodes that are interconnected by fibers in a ring or meshed topology potentially operated in WDM. The wavelengths are terminated in each node and switching is only done in the electrical domain on different levels of granularity. SDH connections of different granularities are multiplexed to higher order connections and transported over one or several SDH cross connects. In SDH cross connects, these signals can be partly or entirely demultiplexed in order to add and/or drop lower granularity signals. On the one hand, this architecture has the advantage of being very flexible in routing connections through the network as the capacity of the links is completely shared among all connections. On the other hand, as the entire traffic has to be converted to

the electrical domain and back to the optical domain, in each node a very high number of O/E and E/O-converters (transponders) is required which is one of the most important cost factors today. Furthermore, instead of bypassing transit nodes the traffic has to traverse all electronic cross connects which increases the size of their switching matrix and the node cost without giving any benefit.

To reduce these two drawbacks, the network is extended to a multi-layer network by adding an optical layer, that allows for optical bypassing without intermediate O/E/O-conversion. This optical plane can be dynamic or in a first step static as discussed in the following:

The first principal network and node architecture is depicted in **Figure 1**. As in the single-layer case, it consists of nodes that are interconnected by fibers or fiber trunks. In the nodes, the SDH layer consists of a non-blocking electrical cross connect (EXC) with switching capabilities for all SDH granularities. In the optical layer, after demultiplexing the wavelengths are either connected directly to the output multiplexer or via a transponder to the EXC. The fixed transponders terminate the wavelengths at a given line rate. In contrast to the single-layer case, wavelengths can transparently pass through the node and only those wavelengths that have to be terminated in the node are converted to the electrical domain while all the other wavelengths bypass the electrical domain without being modified and without occupying any transponders or switching resources there. That leads to a dramatic reduction of the number of required transponders and the size of the electrical cross connect compared to a single-layer architecture. Furthermore, depending on the configuration, the topology of the SDH network is independent on the physical fiber topology and can be arbitrarily chosen during the network design process. Thus, as several SDH connections between the same endpoints are groomed to higher order connections of up to wavelength bandwidth and transmitted using an end-to-end lightpath, usually no intermediate hops are necessary where the lightpath has to be terminated. Although dynamic switching of connections is possible due to the functionalities in the electrical layer, this architecture will be referenced as *static* since the optical layer has no switching resources.

However, as those optical bypasses either have to be installed in advance or reconfigured manually, the network is only dynamic in the electrical layer. The *dynamic* network architecture is shown in **Figure 2** and has an optical layer which is capable of setting up and tearing down on demand transparent lightpaths from any source node to any destination node through the network. With this, the virtual topology on the electrical layer, i. e., the capacity connecting two nodes, can be adapted during operation by adding and removing links. Also depicted is the node architecture which differs from the
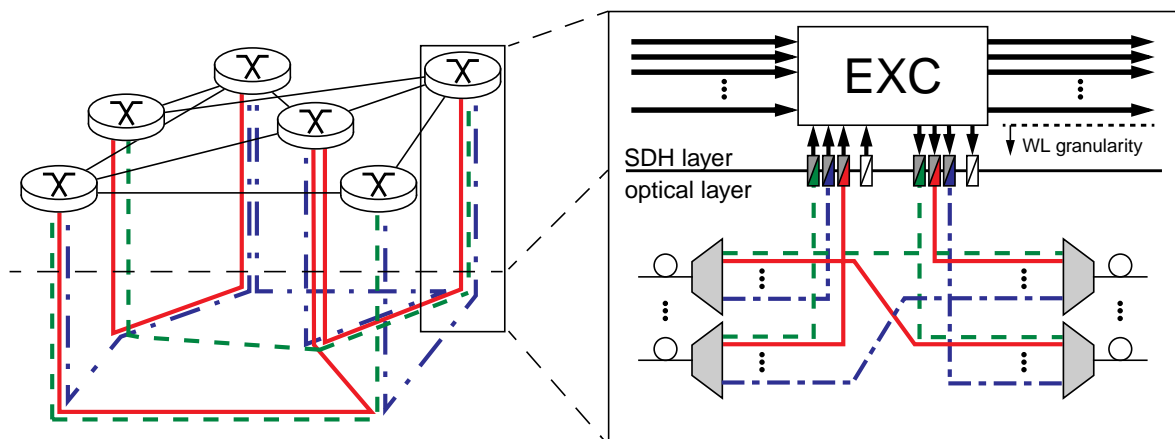

Fig. 1: Network and node architecture for multi-layer networks with *static* optical plane

node of the *static* architecture only in that a wavelength selective non-blocking optical cross connect (OXC) operating on wavelength granularity is used in the optical layer. The EXC and OXC are interconnected by a limited number of tunable transponders at a given line rate. The dynamic multi-layer node offers following functionality:

1. An incoming wavelength channel can be switched directly to an outgoing fiber on the same wavelength.
2. If wavelength conversion is necessary, this can be emulated by switching the wavelength channel to the EXC and without any SDH processing back to the OXC on another wavelength and via the OXC to the output fiber.
3. Wavelengths carrying SDH connections for different destinations can be switched through to the electrical layer for dropping as well as additional SDH connections can be added onto partially used wavelengths.

Comparing the two multi-layer architectures, several major differences can be observed. With respect to functionality, in the dynamic architecture a new degree of freedom has been added as additional lightpaths can be established and unused lightpaths can be removed. Also, the used components vary. In the static case the wiring in the optical layer is fixed. So the wavelengths of the transponders are predetermined and thus, fixed transponders can be used. In the dynamic architecture, the wavelengths of the transponders are selected on demand and thus tunable transponders have to be used. Still, tunable transponders are more expensive than fixed transponders but prices are declining and due to e. g. more efficient stock keeping, operators are willing to pay the higher price. Another difference lies in the OXC. While in the static case either no such component or only a simple wiring panel is needed, this component is more complex in the dynamic architecture. Depending on characteristics like switching speed or number of wavelengths, OXCs are a high cost factor.

In both network and node architectures, the interconnection between the nodes as well as between the cross connects have an impact on the overall performance. Specifically, in the static scenario the number of lightpaths connecting a node pair has to be dimensioned. With this, the demands for the optical layer are known in advance and can be used for dimensioning of fibers. For this, the so called routing and wavelength assignment problem (RWA) must be solved [5]. In the dynamic scenario also the optimal number of transponders and fibers for the nodes and links has to be determined. As the lightpaths are established on demand, heuristics have to be used to calculate the optimized fiber
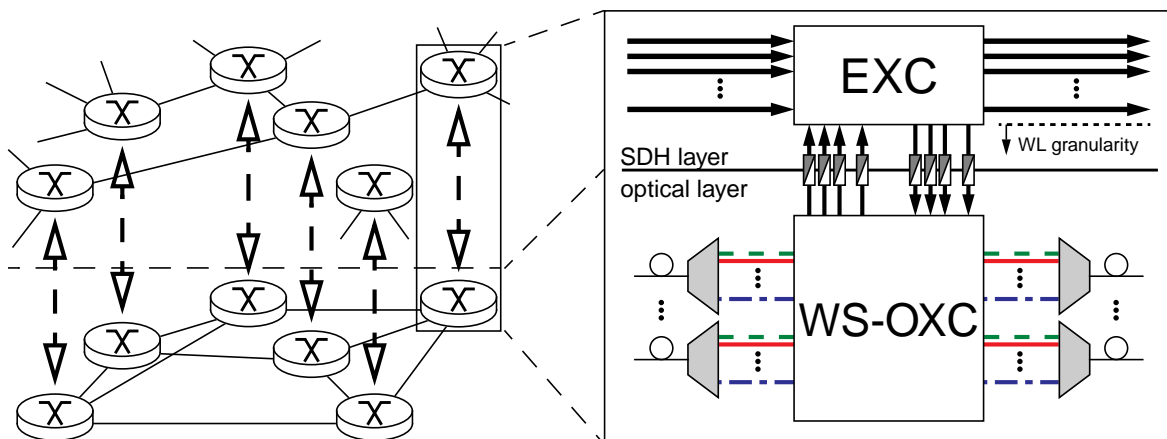

Fig. 2: Network and node architecture for multi-layer networks with *dynamic* optical plane

topology. To be in this paper as general as possible while keeping the number of degrees of freedom on a reasonable level, we assume the optical layer to be infinitely large. This is reasonable as the cost of a multi-layer transport network is mostly dominated by the transponder cost [3]. With this assumption, no influences of specific RWA algorithms and specific dimensioning schemes must be considered. Compared to a scenario with limited resources in the optical layer, the difference will be rather small in the static scenario as the path of a wavelength in the optical layer has no influence on the routing in the SDH layer. In the dynamic case, decreasing the number of fibers will lead to worse results due to blocking in the optical layer if the dimensioning is too tight.

3. Grooming and Routing in Multi-Layer Networks

For each SDH request a path has to be assigned or the request will be blocked. SDH connection requests are determined by the three parameters source node, destination node and bandwidth. Thus, it is necessary to find a path for the node pair with sufficient available capacity. Even more, if more than one path can be found, it is necessary to decide which of the paths should be chosen. In multi-layer networks routing comprises both tasks of path selection in the optical and/or electrical layer as well as grooming.

Path selection comprises the task of finding paths in a given topology between two nodes with given constraints. While in the optical domain wavelength continuity has to be considered, in the electrical domain the available capacity of links has impact on the routing decision. In single-layer networks, only one topology has to be considered whereas in multi-layer scenarios several possibilities arise. Non-integrated schemes treat path search in the different layers separately, integrated schemes calculate the possible paths using all layers in parallel.

Grooming refers to the act of combining low order connections to channels of a given maximum capacity in order to minimize cost for switching. This can be done not only in the source node of a connection, but also in intermediate hops where connections from different source nodes to the same next hop are combined to a new channel for optimized utilization of channels (c.f. [4]).

It can be seen that these tasks are neither in a single-layer network nor in a multi-layer network independent of each other. Accordingly, the path search and grooming schemes have to be harmonized. For single-layer networks, two basic grooming options can be identified that are also the basis for the multi-layer grooming schemes:

A. single-hop grooming on existing lightpath: The connection is assigned to one existing direct lightpath.

B. multi-hop grooming on existing lightpaths: Routing takes place on the electrical layer by using more than one existing lightpath and switching the connection in the EXCs of intermediate nodes.

In case of multi-layer networks, two more options arise:

C. single-hop grooming on new lightpath: A new lightpath is set up between the source and the destination node. The connection request is routed on the optical layer via this new lightpath.

D. combined multi-hop grooming on new and existing lightpaths: This is a combination of options A and C. The connection request can be routed on both the electrical and optical layer by using a series of existing and new lightpaths.

These schemes mainly differ in the layers they are using for selecting the path. The schemes A and B use only the electrical layer and scheme C only the optical layer whereas both layers are used in scheme

D. To define the routing scheme, these principal options can be used alone or in combination in any order leading to different results. We derived the set of principal routing schemes used in this paper as follows:

Single-hop routing (SH) uses only direct end-to-end lightpaths without any intermediate switching in the electrical layer. This scheme first applies grooming option A and if no path was found option C in case of the *dynamic* architecture.

Multi-hop routing (MH) tries to find a path using the switching capabilities in the electrical layer. In the *static* architecture, first grooming option A is used and after this option B. In the *dynamic* architecture, also option C can be used. Here we have to differentiate the order of applying the options. The ordering A-B-C leads to a routing scheme, that first tries to route the connection in the electrical layer and after that tries to setup a new direct lightpath (prefer multi-hop paths, MH-pMH). Applying the grooming options in the order A-C-B leads to a routing scheme that first tries to route the connection on a direct path even if a new lightpath has to be established. Only if this is not possible a multi-hop path is used (prefer new lightpaths, MH-pLP). For all multi-hop paths, the path selection in the electrical layer is done by a shortest path algorithm. So, while MH-pLP minimizes the switching effort in the SDH layer, MH-pMH reduces the number of lightpaths that have to be set up. To reduce the fragmentation of the network for all single as well as multi-hop schemes the *most used* principle (adapted from [9]) will be used for selecting the path if more than one can be found.

In addition, a larger number of more complex routing schemes have been defined in literature. In [15], we presented an integrated multi-layer routing scheme called Weighted Integrated Routing (WIR) that is able to perform the combined grooming described in option D. Among this, other integrated and non-integrated multi-layer routing schemes are defined, e. g, in [17] and [10]. However, our previous work showed that they can only outperform simple non-integrated routing schemes if the number of fibers is limited (c. f. [15] for scenarios with tight transponder dimensioning). So, in this work it is sufficient to investigate only the results of the single-layer schemes as the number of fibers is unlimited as stated above.

4. Performance Evaluation

In this section, performance evaluation by event driven simulation is presented for a Pan European network scenario with a reference traffic mix. We compare the performance achieved using the *static* and the *dynamic* network architecture for different network capacities and show the benefit of a dynamic optical plane. Furthermore, the impact of the traffic mix especially the impact of connections that require a full wavelength is shown. Finally, we investigate the dynamics necessary in the optical layer in order to estimate the viability of manually operated optical cross connects.

A   Model Description

All presented simulation studies were performed in a fictitious 16-node reference network of Europe [12] with 23 bidirectional links shown in **Figure 3**. The traffic matrix was derived from a population model for different traffic types and scaled according to typical growth factors. The line rate was set to 10Gbps (e. g., STM-64/OC192). Two total network capacities are considered: the low capacity network was dimensioned for a total offered traffic of A=4.9 Tbps, which corresponds to the traffic volume expected for 2004. The high capacity network is dimensioned for a total offered traffic of 49 Tbps

expected for 2008. These networks have a mean number of 2.0 and 20.0 lightpaths per node pair, respectively.

All connection requests arrive according to Poisson processes and holding times are negative exponentially distributed. Even if this traffic model originates from scenarios with a large population of traffic sources each contributing only a small amount of traffic, it is a well accepted reference model for core networks and has also been widely used in wavelength routed networks (e.g. [16]). Unless stated differently, we used in the simulation studies the traffic mixes shown in **Table 1** (c.f. [8]). The major difference between mix I and mix II concerns the maximum bandwidth granularity. While mix I contains 20% of STM-64 connections, i. e., a full wavelength, the highest granularity in mix II is STM-16, i. e., a quarter of a wavelength. So, according to [13] which analyzes the bandwidth requirements of connections between metro networks in the U.S. mix II reflects more the traffic requirements of todays services whereas mix I includes also future dynamic high capacity services.

As mentioned above, the number of fibers is assumed to be infinite. Furthermore, in the *static* scenario, the transponders are assigned to dedicated lightpaths. So, the dimensioning of the transponders can be directly derived from the dimensioning of the lightpaths. As presented in [11], we calculate the number of lightpaths between two nodes i and j based on the offered traffic $A_{i,j}$ and the blocking probability B. To achieve the same blocking probability for each node pair, we apply the well known Erlang-B formula to calculate the number of lightpaths per node pair $z_{i,j}$ (**Eq. 1**).

$$z_{i,j} = \mathrm{ErlangB}(A_{i,j}, B)$$
$$\sum_{i,j} z_{i,j} = Z_0 \cdot p \tag{1}$$

We chose the blocking probability B for all node pairs such that the total number of lightpaths in the network is equal to a predefined number Z_0 scaled by the overprovisioning factor p. Z_0 can be interpreted as the total number of transponders in the network for a provisioning of 100% and is dimensioned for static traffic demands.

In the *dynamic* network scenario, the number of transponders has to be dimensioned for each node i. We calculated the number of transponders per node z_i using the same concept described above but instead of calculating the lightpaths per node pair we now calculate z_i based on the total offered load in

Fig. 3: Pan-European Network Scenario

Granularity	mix I		mix II	
	% vol.	% conn.	% vol.	% conn.
STM 1/OC 3	40	93.4	30	80
GBit Ethernet[1]	—	—	40	15
STM 16/OC 48	40	5.8	30	5
STM 64/OC 192	20	0.8	—	—

[1] transported as VC-4-7v in SDH

Table 1: Traffic mixes

the node A_i (**Eq. 2**). The total number of transponders for a provisioning of 100% Z_0 is the same as in the static case.

$$z_i = \text{ErlangB}(A_i, B)$$

$$\sum_i z_i = Z_0 \cdot p \tag{2}$$

Note, an overprovisioning factor of 1.5 leads to a 1.5 times higher number of transponders in the network which does not necessarily relate to individual nodes or node pairs, respectively, due to the non-linearity of the Erlang-B approach.

Two important performance criteria for this type of network are the *SDH request blocking probability* B_u and the *weighted SDH request blocking probability B_w*.

$$B_u = \frac{\sum_i R_i}{\sum_i N_i} \tag{3}$$

$$B_w = \frac{\sum_i i \cdot R_i}{\sum_i i \cdot N_i} \tag{4}$$

Both are calculated based on the number of rejected and arrived connections of granularity i, R_i and N_i respectively, where i is 1 for STM-1, 16 for STM-16 and so on. While the previous refers to the number of rejected connections independent of the rejected traffic volume (**Eq. 3**), the *weighted SDH request blocking probability* also includes the rejected traffic volume (**Eq. 4**). In the following, we will use B_w as the carried traffic volume is the more relevant performance metric.

All graphs also contain 95% confidence intervals based on the batch simulation method. In **Figures 10** and **11** no error bars are shown as they are derived from other statistics.

B   *Low Capacity Network*

In this section, we present the principal behavior of the single and multi-hop routing schemes for the different traffic mixes in the low capacity network. In **Figures 4** and **5**, the mean weighted SDH request blocking probability is plotted versus the overprovisioning factor for traffic mix with and without wavelength requests respectively. It can be seen that in both cases the weighted SDH request blocking probability is smaller for the dynamic case than for the corresponding static case.

In **Figure 4**, in the scenario with wavelength requests, i. e., traffic mix I, the performance for low overprovisioning factors is almost independent of the routing scheme. Only a small gap can be seen between the multi-hop schemes and the single-hop schemes. For high overprovisioning factors the results differ clearly. Single-hop routing in the static case has the worst performance. The reason is that for each node pair only a fixed number of lightpaths shared among all the connections can be used. If these lightpaths are completely used or the available capacity is smaller than the required bandwidth, a new connection request is blocked. In contrast, multi-hop routing can benefit from detours although some additional load is introduced into the network. In the dynamic scenario, the routing schemes

preferring direct paths (SH and MH-pLP) have almost the same performance. Compared to the static case, the blocking probability is reduced as the capacity between the nodes can be adapted to the current requirements. Only the routing scheme MH-pMH, that preferably uses multi-hop paths has a worse performance. This can be explained by the high number of detours leading to a high additional load in the network that reduces the performance.

In **Figure 5**, without wavelength requests, i. e., traffic mix II, the results differ. For low overprovisioning factors, the multi-hop routing schemes lead to a worse performance than the single-hop schemes. The reason can be found in the additional load introduced by detours and thus blocked resources that are needed for other connections. While this penalty was very small in case of traffic mix I, now the gap is clearly observable as connections of full wavelength capacity never use multi-hop paths and thus never introduce additional load. For high overprovisioning factors, the multi-hop routing schemes MH-pLP in the dynamic case and MH in the static case outperform the single-hop schemes. Furthermore, it can be observed that for the single-hop schemes the blocking probability decreases slowly whereas for the multi-hop schemes preferring single-hop paths after reaching a certain level of provisioning, the curves drop very quick. This will be discussed in detail in Section C

Comparing the results of the traffic mixes, it can be observed that traffic mix I has always higher blocking probability than traffic mix II for the same total offered load. The reason for this is the domination of wavelength connections in traffic mix I, that will be discussed in the following sections.

Now, going into detail, the behavior of the different granularities will be explained. **Figures 6** and **7** depict the distribution of blocked calls for the different routing schemes, that is $R_i / (\sum_i R_i)$, versus the overprovisioning factor for traffic mix I and traffic mix II, respectively. As the results for the static and dynamic case are almost the same, we only present the static case for clarity.

In general, it can be observed that with increased overprovisioning factors, high capacity connections are more often blocked whereas low capacity connections perceive a good service. Especially in the case of multi-hop routing in the case of traffic mix I for a provisioning of more than 1.4 only wavelength connections are blocked.

For multi-hop routing, we can see, independently of the absolute granularity for high overprovisioning factors, that almost only connections of the highest granularity—that is full
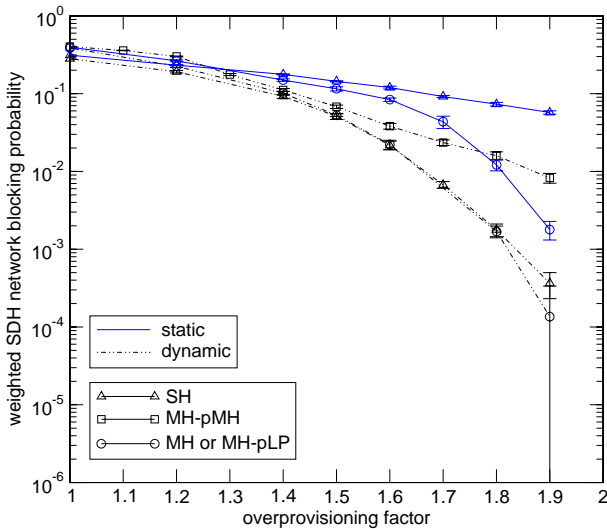

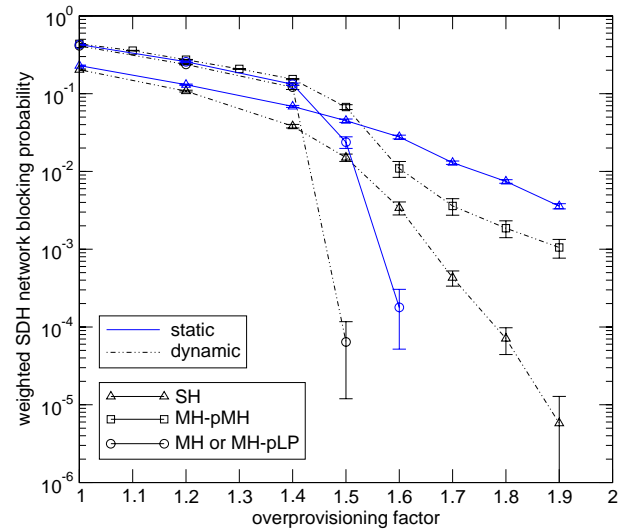**Fig. 4:** Results for low capacity network with wavelength requests (traffic mix I)

Fig. 5: Results for low capacity network without wavelength requests (traffic mix II)

wavelength and quarter-wavelength, respectively—are blocked. For traffic mix I, the high capacity connections dominate the blocking probability and limit the network throughput as they require entire wavelength channels whereas the other granularities can use the available bandwidth of partially used channels. For traffic mix II, the explanation is not so self-evident as all the connections can use partially used wavelength channels. But the probability for finding a path with at least the required bandwidth unused decreases with the increase of requested bandwidth. So, not only STM-16 connections are blocked but the number of connections is much higher than the number of GbE-equivalent connections. For low overprovisioning factors, applying the multi-hop schemes only the connections of the smallest granularity STM 1 are not blocked whereas all the others are blocked. Here, the network dimensioning is too tight in general and thus, only for the very low capacity connections a path can be found. Single-hop routing leads to a different behavior. It can be seen that, independently of the provisioning all types of connections are blocked. For high overprovisioning factors a separation can be noticed, that is larger for traffic mix I than for traffic mix II.

C Impact of Network Capacity

In this section, we investigate the impact of the network capacity. Thus, we also use here the high capacity network. **Figures 8** and **9** depict the weighted SDH request blocking probability versus the overprovisioning factor as it was shown above for the low capacity network. While for the small network an overprovisioning of more than 50% was required to reach an acceptable performance, now only an overprovisioning in the range of some 10% is needed for blocking probabilities below 1%. This can be explained by the economy of scale as for a small offered traffic and a small server bundle the relative increase of the server bundle is higher than for a high offered traffic and a large server bundle if the blocking probability before and after changing the server bundle is the same.

As in the low capacity network, it can be observed that for small overprovisioning factors single-hop routing leads to a lower blocking probability than the multi-hop schemes preferring direct paths whereas for higher overprovisionings the results are vice versa. In contrast to the low capacity scenario, this can be observed for both traffic mixes—with and without wavelength requests. Furthermore, while
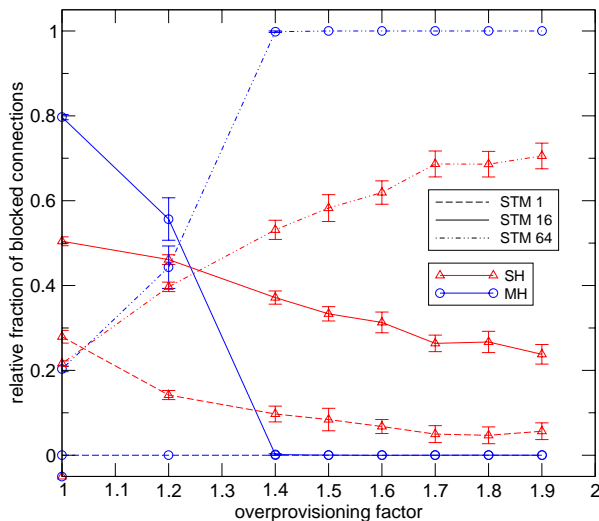

Fig. 6: Distribution of blocked calls for low capacity network with traffic mix I
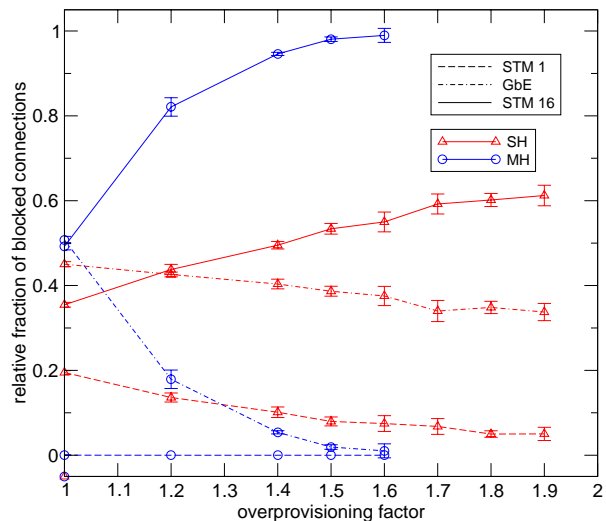

Fig. 7: Distribution of blocked calls for low capacity network with traffic mix II

in the low capacity scenario MH-pMH leads to a better performance than the single-hop scheme in the static case, now the performance is always worse.

For the multi-hop routing schemes preferring a direct paths, i. e., MH in the static case and MH-pLP in the dynamic case, the immediate dropping of the blocking probability reaching a certain amount of overprovisioning can be seen independent of the traffic mix. We observed this effect often in this context in other scenarios as well as in the OBS scenario [6], [7]. The multi-hop routing schemes have a large number of possibilities for detouring a connection in case of being blocked on the shortest path. Above a certain threshold of provisioning, the probability of blocking is very low and almost all connections are established on the shortest path. Below the threshold, the probability for blocking raises very fast due to positive feedback [14]. Here, many paths of connections contain detours. In general, detouring leads to increased traffic and thus a higher blocking probabilities on the shortest path which again increases the number of detoured connections etc. Concluding, a large number of connections is not established on the shortest path anymore leading to an increased load and a highly congested network with a high number of connections rejected.

D   Impact of Wavelength Requests

In the previous sections, we have often shown that the difference between the static and dynamic case depends on the existence of connections that need an entire wavelength. Therefore, in this section the impact of the amount of connections of this type on the required provisioning shall be systematically investigated. The traffic mixes we use here are derived from traffic mix I. Instead of using a fixed fraction of wavelength connections, we vary this from 0 to 100%. As for the original traffic mix I defined, the volume of STM 1 and STM 16 traffic is equal and sums up the mix to 100%. **Figure 10** depicts for the static and the dynamic case the required overprovisioning for a weighted SDH blocking probability below 10^{-2} which is an acceptable value for such future networks according to operators versus the fraction of wavelength connections. The routing schemes MH and MH-pLP are used for the static and dynamic case respectively.
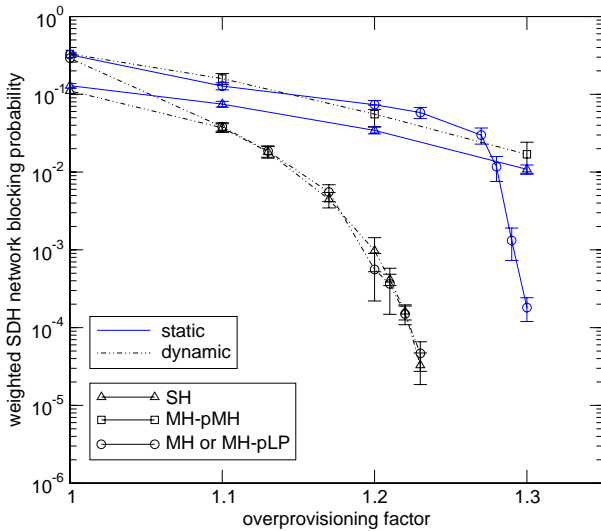

Fig. 8: Results for high capacity network with wavelength requests (traffic mix I)
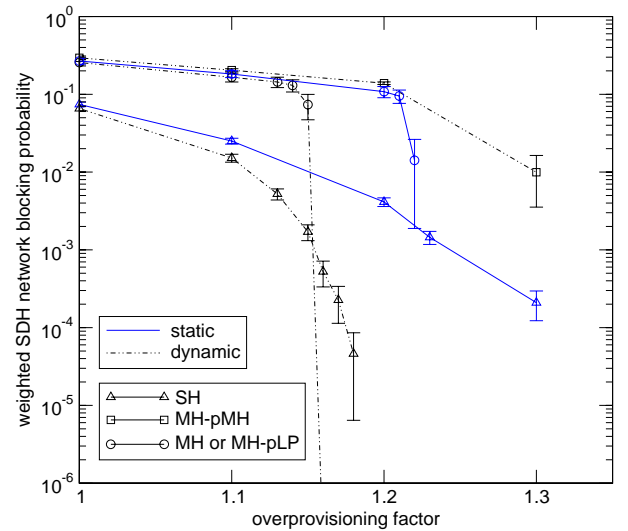

Fig. 9: Results for high capacity network without wavelength requests (traffic mix II)

For the dynamic case, the required overprovisioning grows slowly for a small number of wavelength connections and is almost stable for a wide range of traffic mixes, i. e., from 20% to 95%. Furthermore, a decrease in required overprovisioning can be observed for a traffic mix containing at least 95% wavelength connections.

As soon as at least a small fraction of low capacity connections is in the traffic mix, lightpaths usually are not fully utilized. The remaining capacity of these lightpaths can not be assigned to connections with high bandwidth requirements leading to a virtually lower overprovisioning for the wavelength connection requests. Thus, the provisioning required for a traffic consisting only of wavelength connections is lower than for the same volume of a traffic mix with few low capacity connections.

In the static case also the knee for very low and very high fractions of wavelength connections can be observed. But while in the dynamic scenario the required overprovisioning was almost insensitive to the composition of the traffic mix for a wide range, in the static scenario the required provisioning increases with increasing the ratio of wavelength connections unless reaching 95%.

E   Dynamic behavior of optical layer

Comparing the two cases of static and dynamic optical plane, the dynamics of the OXC necessary for realizing the improvements becomes interesting as this can give a hint about the cost for the optical plane. **Figure 11** depicts the mean number of new SDH connections established between the setup of two lightpaths versus the overprovisioning factor. The lightpath setups for wavelength requests are not included. In general, the lower this mean value, the higher is the dynamic.

In case of high overprovisioning, two groups can be identified. While the dynamics for MH-pMH is rather low, the routing schemes preferring single-hop paths have a higher dynamic in the optical plane. As defined MH-pMH preferably uses multi-hop connections. So if sufficient capacity is available, existing connections are used instead of establishing new ones. SH and MH-pLP in contrast establishes new connections leading to a higher dynamic in the optical layer. For low overprovisioning, SH has the highest dynamic, followed by MH-pMH and MH-pLP. In case of SH routing, the lightpaths between a pair of nodes are not shared with other node pairs. The probability for emptying a lightpath and in the
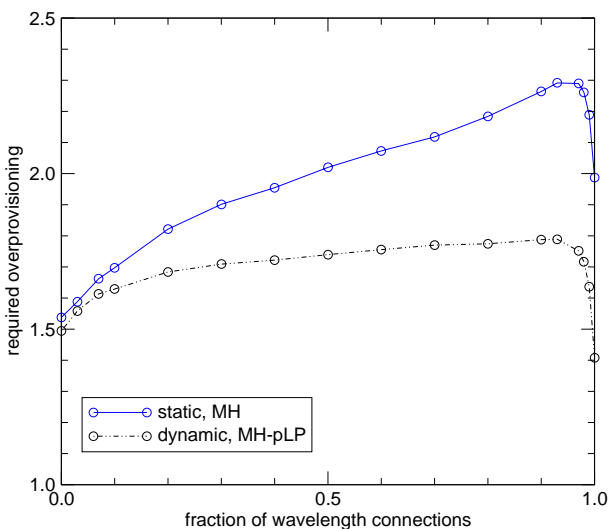

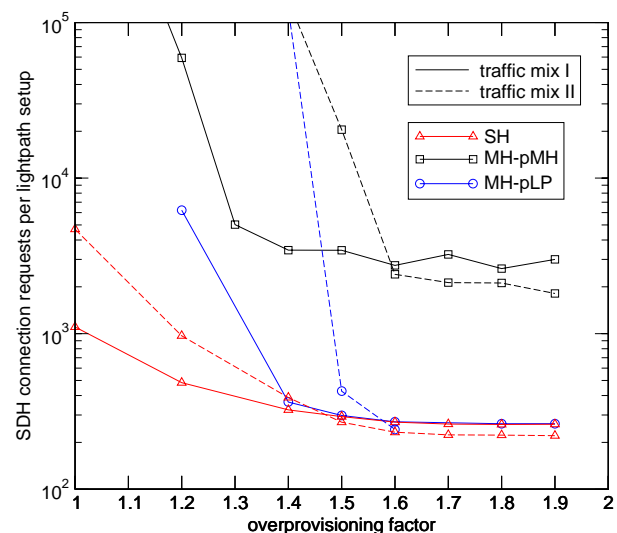**Fig. 10:** Impact of wavelength connections

Fig. 11: Dynamics in the optical layer for low capacity network

following tearing down is rather high compared to the multi-hop schemes. The multi-hop schemes on the other hand share the lightpaths between a node pair among all node pairs. Thus, if the resources are tight, the lightpaths are torn down only seldom or even never leading to low or no dynamic. Finally, for the traffic mix I with wavelength requests the dynamic is higher then for traffic mix II for low overprovisioning factors while for high overprovisioning factors, the situation is vice versa.

Concluding, in the worst case of highest dynamic, every 200 SDH connections a new lightpath is set up or torn down. Assuming the time between two connection requests to be in the range of minutes, which is according to discussions with operators a feasible timescale, in such future networks every hour a new lightpath has to be switched through at least two optical cross connects motivating the use of automated switches. Alternatively, the routing schemes have to be designed to choose the paths not with respect to a maximized network utilization but to minimize the number of switching events in the optical layer.

5. Conclusions

In this paper we introduced the network and node model of a multi-layer network with a static and a dynamic optical layer. We discussed and evaluated basic grooming and routing strategies for this network. In our performance evaluation we showed the principal behavior of the routing schemes with respect to the network capacity and the traffic composition. Also, the influence of high capacity requests on network dimensioning was studied. Finally, studies on the number of lightpaths to be switched in the optical layer were presented.

We showed that for a low overprovisioning a single-hop routing scheme outperforms multi-hop routing schemes whereas for a high overprovisioning a multi-hop routing scheme that prefers direct lightpaths has the best performance. With respect to the total capacity of the network, the overprovisioning has to be chosen carefully as a small modification of the capacity can change the performance by several orders of magnitude.

Concluding, the traffic mix has a significant impact on the performance of static and dynamic multi-layer networks. A network with a dynamic switching optical layer can cover changes in the traffic mix very well, however, at the cost of increased complexity of required components as well as of routing. Assuming the traffic mixes used in this paper represent todays and future requirements, it can be a solution to first introduce nodes with a transparent static optical plane and when high bandwidth requests come into the network extend the nodes by a dynamic switching optical layer. However, the performance benefits can not be the only driver to bring dynamic optical cross connects into the field. Still, other value adding features e. g. restoration of entire fibers or lightpaths will be an argument.

Acknowledgment

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