Applying statistical multiplexing and traffic grooming in optical networks jointly

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Multilayer optical core networks are able to provide huge bandwidth. With traffic grooming we can utilize more efficiently the available resources. The principle of grooming: if the routes of two different traffic flows (or demands) have common links, their traffic can be joined in to the same wavelength channel. Another well-known solution for increased efficiency of resource usage is multiplexing the traffic. The statistical multiplexing does not allocate the maximal bandwidth for each traffic demand, but less than the maximal and more than the average. The aim of this article is to investigate the effects of applying both solutions.

1. Introduction

The optical core networks are based almost exclusively on optical transmission, because this technology provides huge bandwidth: A single optical channel typically carries data at a rate of 10 Gbps. In addition, the application of Wavelength Division Multiplexing (WDM) enables that a fibre can transmit more simultaneous signals using parallel channels. Depending on the number of parallel channels we differentiate Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM) systems. In DWDM systems more Tbps can be provided.

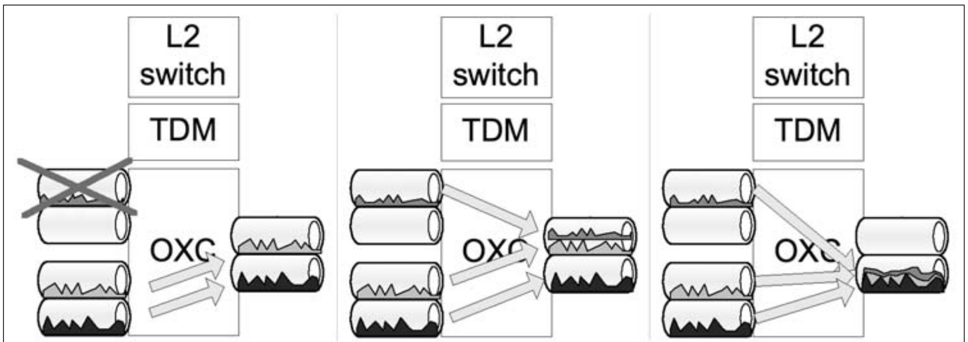
In such DWDM networks connections between distant nodes are realized using lightpaths that may be defined in advance or on-demand. Each lightpath is a sequence of wavelength channels and traffic enters and leaves it only through its endpoints, so these lightpaths can be imagined as pipes laid in the network. The clear purpose of the operator in such networks is to use the available resources efficiently via properly configuring the lightpaths. The network operator faces two problems related to resource allocation:

(1) the traffic demands have bandwidths by orders of magnitude lower than the size of a wavelength channel, and (2) the traffic rate fluctuates, so it does not use the whole allocated bandwidth in the significant part of time. The first problem is solved by the traffic grooming concept [2], while the second is by statistical multiplexing. The two areas have own considerable literature, but as far as we know the effects of joint application of these two solutions haven not been investigated in switched optical network, yet. We aimed this problem in our article.

We illustrate the above problem through the following example. *Figure 1.* depicts a node with three ports and each port has two wavelength channels. The traffic arrives from three different sources while their destinations (or the next node along the paths) are the same. The traffic from three sources arrives on different wavelength channels.

If wavelengths switching is allowed only (Figure 1.a), then only two of the three flows can be forwarded, thus, the third flow would be blocked at connection setup phase. If traffic grooming is supported, the traffic of all three sources could be combined to one channel. However, the sum of the maximal bandwidths given by traffic descriptors exceeds the capacity of the outgoing wavelength channel; therefore, only two of the three flows can be groomed into one channel and a further channel will be defined for the third flow (Figure 1.b). Finally, if we allow that less than the sum of the maximal bandwidth requirements is allocated – the exact method of how to calculate this value will be detailed later –, then all the three traffic flows can be carried in the same channel (Figure 1.c).

Figure 1.
Joint application of grooming and statistical multiplexing based aggregation for switching



a. Wavelength switching   **b.** Traffic Grooming   **c.** Grooming and aggregation

Whenever, only whole wavelengths can be switched (there is no grooming), considering statistical multiplexing is meaningless in this example, since the three flows arrive in different channels and they cannot be groomed, so there would be no multiplexing gain at all.

2. Resource allocation and routing in switched optical network

Static resource allocation in switched optical networks is used, when the traffic demands are static, i.e., neither their bandwidth nor their endpoints change. The traffic matrix formed by these demands is constant: it can be defined in advance. In this case traffic routing problem can be formulated as an optimization task and good or even optimal solution can be found. On the contrary, in real networks the traffic demands arrive in different moments, and after different holding times they leave the network. It can be better described using a dynamic allocation model, where both the intensity and the space distribution of the traffic varies in time. In that case the arriving traffic demands are served in sequence one after the other.

2.1. Wavelength graph model

For the formal description of the dynamic routing we assumed the Wavelength Graph model. The base idea of this model is that the fibres between two nodes are modeled by many parallel edges as different wavelengths are used over that fiber. In addition all physical nodes are described with type-dependent subgraphs that make possible to describe different types of nodes in simple and expressive way. This property is one of the most important benefits of this model. In this paper we assumed two node types with different abilities:

The optical cross connects (OXC) realize switching whole wavelength channels between fibres. Additionally they have optical add-drop multiplexer (OADM) functionality in order to act as ingress and egress points for the traffic demands. On the contrary, *the grooming nodes* complete the property of OXC nodes; the grooming nodes can multiplex more traffic in one common channel, so they have grooming capability. The grooming is detailed in the next section.

2.2. Traffic grooming

The bandwidth requirements of traffic demands are typically less than the capacity of a wavelength channel. A whole channel assigned to one traffic demand wastes the resources in most cases, therefore, the ligthpaths should be shared among more traffic demands. When two or more demands have the same source and the same destination they can be *multiplexed* in the electronic layer of the ingress node and transferred along one ligthpath. At the egress node they can be de-multiplexed. However it cannot be applied in the case, when the traffic demands do not have the same source or destination.

In this latter case, the ligthpaths have to be torn down before and after the common part of their paths and at this point the traffic is transmitted to the electronic layer. The traffics are multiplexed there – e.g. by using time division – and in the common part transferred in one channel. This solution is referred as *traffic grooming*. In general traffic grooming is, when the traffic arriving from one or more channels is rearranged in higher – electronic – layer (e. g. according to their destination), and they are forwarded in a common channel combined together.

The clear benefit of grooming is the efficient usage of wavelength channels. However, at the same time the grooming requires expensive optoelectronic converters to route the traffic to the electric layer. Therefore in the dimensioning phase the cost of the grooming must be taken into account. Nevertheless, in this paper we do not deal with these design and dimensioning questions.

2.3. Statistical multiplexing

Significant part of the traffic in the core network is provided by data traffic, which has rate variance in time. This raises an issue of how much capacity should be allocated for the traffic demands? Traditional solution is to allocate resources equal to the sum of maximum bandwidths required by each demand. This is *deterministic multiplexing* that results in an over-dimensioned network. The amount of over-provisioned capacity can be decreased with the application of statistical multiplexing (or aggregation). In this case we exploit that more sources likely do not generate traffic at peak rates. So for the aggregated traffic a limit can be defined, for which the probability of aggregation extending the defined limit is a fixed low value. This latter parameter is the *overflow* (or the packet loss) *probability* and the name of the defined limit is *effective bandwidth*.

The theoretical principles can be found in F. Kelly's paper [4]. S. Floyd has proposed a simple method for defining the necessary capacity based on the Hoeffding bound:

$$BW = \sum_{i=1}^{n} m_i + \sqrt{\frac{\ln\left(\frac{1}{\varepsilon}\right) \cdot \sum_{i=1}^{n} p_i^2}{2}}, \qquad (1)$$

where m_i and p_i are the average and the maximal rate of the ith basic flow, and ε is the probability that the aggregated traffic exceeds the allocated capacity denoted by *BW*. It has two benefits: it is easily calculable and it is a conservative estimation (it guarantees that after the given border condition the bandwidth will not be larger than the calculated value). Serious drawback is that this model is rather inaccurate in core networks, since the traffic is already aggregated, so the fluctuation is smaller. Therefore, this model is not applicable.

To construct more accurate models we have to make assumption about the characteristics of the traffic. We assume that the arriving traffic flows are mutually independent and their sizes follow the Gaussian distribution. This assumption approximates well the reality, because the traffic of each demand is also aggregated. In this case the Guerin model is applicable [6]. The allocated bandwidth can be calculated as follows:

$$BW = \sum_{i=1}^{n} m_i + \alpha \cdot \sigma, \qquad (2)$$

where m_i the average rate of the elemental sources, while σ is the deviation of the rate of the aggregated traffic. Since more basic and independent flows are assumed for each demand, the aggregated traffic will also follow the Gaussian distribution. This distribution remains when these flows are further aggregated. In this case the overflow probability (i.e., the probability that the aggregation exceeds the allocated capacity) is well characterized with parameter α. For instance, in order to keep the overflow probability at 0.01, the value of alpha must be 2.32, and in the case $\alpha = 5.61$, this probability will be 10^{-8}. Since an additional assumption is that all elementary streams are mutually independent, the variance of the aggregate is easy to calculate: it is equal to the sum of deviations of the elemental traffics.

In [7] an extension of this model is discussed, and it introduces several methods to calculate the α parameter. The benefit of this model is that the effective bandwidth can be easily calculated; furthermore, it describes well the real traffic. At the same time among the traffic descriptors the deviation of the traffic has to be given as well, or should be estimated from the other given parameters (e.g. from average or the maximal rates).

The principle of Lindberger's approximation is that it replaces the original cell rate distribution by a process composed of equivalent Poisson bursts [8]. The resulted formula defines the needed bandwidth for each elemental traffic flow. Summarising this we get the following formula, which is proportional to the average bandwidth requirement and to the variance, and inversely proportional to the capacity of the channel *(C)*:

$$BW = \sum_{i=1}^{n} a \cdot m_i + b \cdot \frac{\sigma^2}{C}, \qquad (3)$$

where *a* and *b* depend only on the packet loss probability:

$$a = 1 - \frac{\log P_{loss}}{50}, \qquad b = -6 \cdot \log P_{loss}.$$

In our examination we used the (1,18; 63) pair of parameter, with which the accessible overflow probability is $P_{loss} = 10^{-9}$.

With the following capacity estimation formula (PCRSCR) the allocated capacity is equal to the sum of the average bandwidth of each demand, and this amount has to be increased with the maximum among the difference of maximal and average bandwidths.

$$\sum_{i=1}^{n} m_i + \max_{i=1..n} \{p_i - m_i\}. \qquad (4)$$

Beside the models discussed here, several other models are known; however, their computational complexity is larger than these models. Nevertheless, our aim is to investigate the effects of introducing statistical multiplexing in optical networks having grooming capability and not to compare the different models.

However, the model proposed by S. Floyd works well only when the traffic flows has great variance: their peak rates are significantly higher than their mean rates. Here, in core networks the traffic flows are already aggregated, so their fluctuation is smaller. Because of this problem, the Floyd model has to be excluded. Hence, we focus on the three other models: the Guerin, the Lindberger and the PCRSCR ones.

3. Investigation of common usage of statistical multiplexing and grooming

The performance of the joint application of grooming and statistical multiplexing was investigated through simulation. For the simulation we have applied a simulation tool called Intra- and Inter-Domain Routing (IIDR). The IIDR is a discrete event simulator developed at our Department. It simulates among others the dynamic behaviour of a given network for different traffic loads.

The network provides connectivity between distant nodes and capacity is allocated for them. The parameters of the connections source and destination address, holding time, average and maximal bandwidth requirements define a *traffic demand*. During the simulations these demands arrive one after the other into the network and the routing algorithm serves them one by one. In the first step it looks for a path between the source and the destination nodes. Searching the route is performed over the logical graph, which is based on the previously introduced wavelength graph. Before the path searching for a demand, the edges having insufficient amount of free capacity are pruned temporarily from the graph. Along the paths found in this reduced graph there will be enough free capacity for the demand, therefore, a shortest path finding method (e.g., Dijkstra's) can be used. If a route exists between the source and destination pair the required amount of capacity can be allocated. Otherwise the demand will be blocked avoiding the latter congestion. In the case of *deleting* a demand the simulator frees the resources allocated to the demand in one step.

The effects of the different investigated aggregation models appear in the routing step. To check whether there is enough free capacity on the link is performed as follows. For each link the algorithm calculates how much capacity would be allocated if the demand to be routed was used the considered link. If this estimated bandwidth is less than the link of the capacity, free capacity will remain after routing the demand. Otherwise, there is no room for the demand on the considered link, thus, the link will be temporarily pruned form the graph.

3.1. Simulation environment

The performance evaluation is conducted in three steps. First, the traffic demands are generated in advance by an application developed for this purpose making possible to perform more independent simulations on the same traffic sequence. Second, the simulations were performed using the generated traffic patterns. Finally, the collected results were evaluated.

3.2. Topologies

We conduct simulations on the reference network of COST 266 European Union project [8]. We used two versions: The first is the COST 266 core topology and the second is the COST 266 ring topology. A core topology consists of 16 nodes and 23 edges, the degree of the nodes less than three. The ring topology consists of 28 nodes and 35 edges, here the average degree of the nodes is 2.5. In the case of both topologies 4 wavelength channels are defined between each pair of nodes, and the capacity of a channel is 1000 Mbps.

3.3. Traffic demands

The traffic demands are described using six parameters: the source and destination nodes, the time when the demand is invoked, the holding time, and finally, the bandwidth requirement of the demand defined by its peak and its mean rates. The demands to be routed are generated randomly in advance to make possible the investigation of the different models over the same traffic sample. These samples are defined as follows. The arrivals are modeled as a Poisson process: the intensity is the inverse of the average interarrival time of consequent demands. The average of the holding time of the demands is also defined. The two descriptors of the bandwidths of demands are calculated as follows: The average peak rate is calculated from the link capacity and it is described with the peak-rate to channel capacity ratio (PCR/CH ratio). The mean rate is derived from the peak rate via multiplying the peak rate with the peak-to-mean ratio (PCR/SCR ratio).

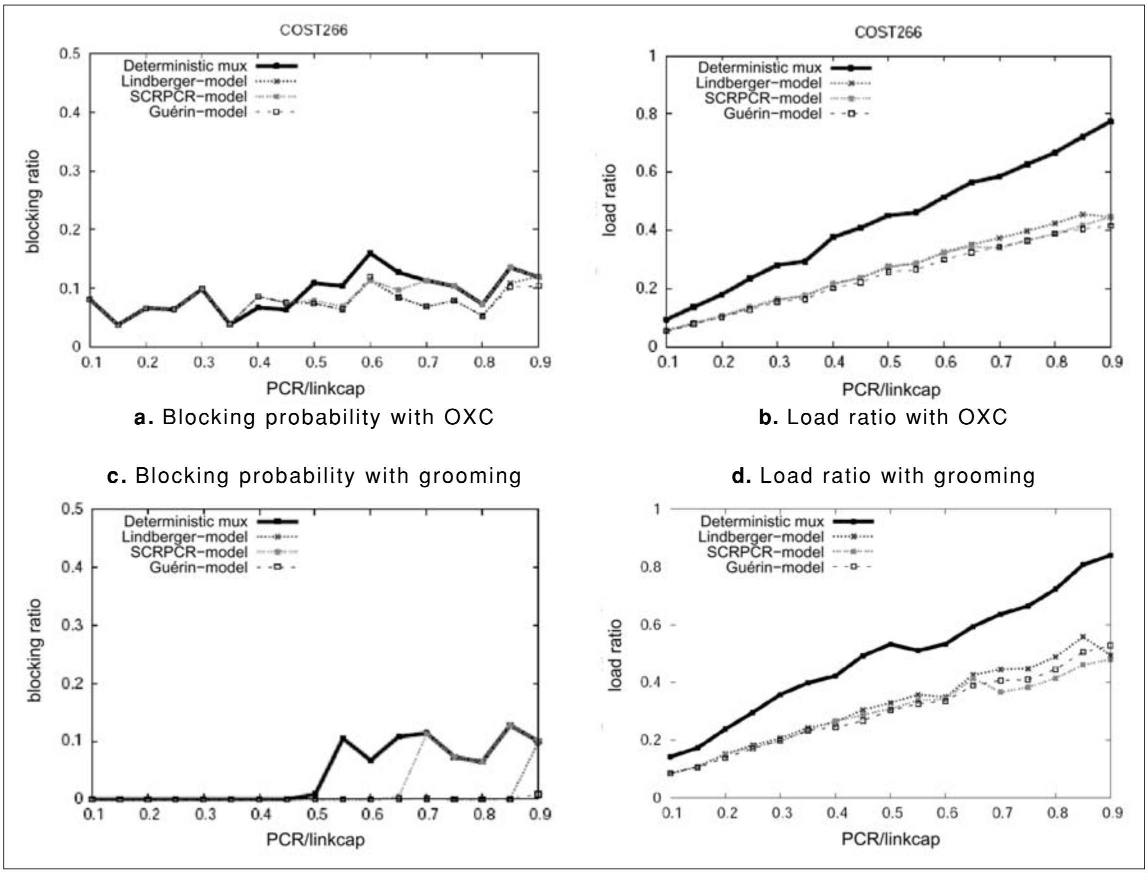
3.4. The investigated parameters

Blocking probability is maybe the most important property from the point of view of the network operation. It indicates how many traffic demands could be served by the network and how many remain *blocked*. If the blocking probability is less, then more demands can be served on the given network, which can result higher income.

Load ratio shows the average load of the network links. This parameter is a good *estimator* of the efficiency of the model and of the method applied. Since there are lightly loaded links in the network, they can serve more traffic, i.e., more demands. Therefore, it also decreases the blocking probability.

4. Results

The simulations are performed on both topologies. In the case of both topologies we define two basic *cases*. In the first case the nodes were OXCs, while in the second one the nodes had grooming capability. In these four base cases we measured the blocking probability and the load ratio. To describe the size and the dynamicity of the traffic we have introduced two metrics: the ratio of maximal bandwidth requirements of demands to the capacity of the wavelength (load), and the ratio



a. Blocking probability with OXC
b. Load ratio with OXC
c. Blocking probability with grooming
d. Load ratio with grooming

Figure 2.

of the average and the maximal sizes of the demands (variability). We investigate the blocking probability and the load ratio by changing these two parameters. On both topologies we have obtained similar results.

In the following simulations we varied the ratio of the size of each traffic demand to the channel capacity from 0.1 to 0.9. Additionally we assumed the ratio of the maximal to average bandwidth, so the variability was 2:1. The next figures show the results *(Fig.2.)*.

Let us assume that all nodes in the network have only wavelength switching capabilities, i.e., all nodes are OXCs. We have measured that difference between the network capacities allocated using deterministic and statistical multiplexing models steadily increases (see Figure 2.b). However, this capacity save is in vain: the blocking probabilities are roughly the same in all multiplexing models (Figure 2.a).

If all nodes have grooming capability a bit higher network load is measured (see Figure 2.d.) compared to the OXC case. However, in this case the capacity save greatly affects the blocking probabilities (see Figure 2.c): the deterministic multiplexing starts to block when the peak rate of a traffic flow reaches the 50% of the link capacity, while the blocking probabilities of the various statistical multiplexing models is roughly 0. These models start to block at higher peak-to-link-capacity ratios. First the SCRPCR blocks at 65%, and then the Lindberger and the Guerin at 85%. When the demands start to be blocked, then the number of traffic demands routed in the network also decreases. This results in the load drops observed on Figure 2.d.

The above measurement we executed by different variability of the demands. Our experiences show that, increasing the variability of the traffic the statistical multiplexing was more efficient against the deterministic multiplexing when grooming is allowed.

We can also see that, when OXCs are used there is no significant aggregation gain, so we cannot serve more traffic in the network. On the contrary, with traffic grooming the blocking probability decreases significantly in the investigated cases, so we can serve more traffic.

5. Conclusion

In this paper we investigated the joint application of traffic grooming and statistical multiplexing in multi-layer optical core networks. In the first step we presented the topic of optical core network focusing on traffic grooming and statistical multiplexing. The purpose of this paper is not the presentation of the entire *storehouse* of the models, hence we selected four approaches to investigate. The dynamic behaviour of the network is evaluated by simulations performed by a simulator tool developed at the Department. The simulations showed that, if the traffic is multiplexed (without grooming), then the gain of statistical multiplexing appears only as a decrease of the allocated resources, but the blocking ratio remains the same. Therefore more traffic cannot be served by the network.

We had expected that applying statistical multiplexing with traffic would decrease the blocking probability. In the paper we showed that, this difference can be large: e. g. with Guerin's model the network starts blocking at 0.9 PCR/linkcap load value (the ratio of maximal bandwidth requirement of traffic to capacity of one channel), while with deterministic multiplexing already at 50% of link capacity.

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