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Performance modelling and analysis of IP over WDM networks

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1 Introduction

Networking is one of the most important challenges of the information society evolving in our days. The fast and safe transfer of sometimes huge amount of data is one of the key functions of many current applications. The communication is indispensable in the working processes based on shared knowledge by users often geographically scattered.

A very important objective in the design and operation of telecommunication networks is the effective use of the available resources. The support of the performance analysis is essential both in the network design and monitoring tasks. Its role becomes even more important if any component of the system works in dynamic manner. The analysis of the *general routing problem* that includes the route selection on a given topology and some technology-dependent tasks like wavelength assignment, grooming etc., needs rather complex performance studies.

Among the fix, cable based, non-local telecommunication architectures used for networking, the one with the brightest perspectives is the TCP/IP based internetworking over static or dynamic wavelength division multiplexing optical networks called IP over WDM. To analyse these networks a model is applied that accords to the architecture presented in [1]. In this multilayered solution the underlaying layer provides high capacity connectivity by establishing optical connections that may span large physical distances. The upper layer provides resources and networking functions to the applications using several transport protocols based on IP. In our general network model we refer these two layers as *optical layer* and *data layer* respectively.

The *optical layer* can be interpreted as a dynamically switched optical core network, e.g. ASON, that consists of optical links and switching nodes, which model OXC, OADM or ROADM devices. The optical links contain several fibers, their number can go up to hundreds in one link. Each fiber can transport data on several wavelengths. A wavelength realises a high capacity optical channel on the link. A connection through a contiguous series of optical channels with equivalent capacity is called *lightpath*.

The main resources in the *data layer* are the routers in the nodes and the links providing bandwidth capacity for both guaranteed or best effort type user traffic. In some of the network nodes there are special switching equipments, G-OXC devices that are necessary to harmonise the tasks of both layers and to perform the data transfer among them. The low bandwidth user traffic will be multiplexed on the high bandwidth optical channels and this is the main goal of traffic grooming.

The logical connection between the layers is the mapping of the *lightpaths* to the links of the *data layer* topology. Since we assume the WDM layer to be dynamically reconfigurable, the topology of the IP layer can change dynamically as well, and can be interpreted as a virtual topology.

The compound analysis of the network that consist of two layers may lead to very complex modelling tasks. Depending on the considered cooperation model of the layers, the *general routing problem* may include multiple functions, thus enlarges also the solution space to be studied. Using a compound model, also the separation of the effects caused by each cooperating function becomes rather difficult.

We can focus the analysis on particular issues of the layers in a more effective way following the method of decomposition and observe the network layers separately. The performance of not compound, i.e., single layer routing functions can be analysed easier this way, since it remains tractable how the algorithm settings affect the measures. The possible decomposition results in two network scenarios to analyse: WDM network with fix topology in the *optical layer* on the one hand and IP network with fix topology in the *data layer* on the other hand. Several works were presented on possible solutions and on studies of the one and the other environment, e.g., in [2, 3, 4, 5, C3] and [6, 7, 8, J3, C6] respectively.

However, there are questions that refer the cooperation issues between the layers where the compound analysis is surely indispensable, e.g. the grooming problems. In these cases the IP over WDM network has to be modelled using fix topology in the *optical layer* but variable topology in the *data layer*. Many grooming algorithms were proposed and compared one another in recent years, e.g., [9, 10, 11], but most of them do not consider the special characteristics of Internet traffic.

2 Research objectives

According to the above outlined issues three main objectives could be identified:

1. The first aim was to develop a more general theoretical model that can be applied effectively in the performance analysis of the *optical layer*. I have

elaborated a technique to calculate the blocking probability of optical channel requests in dynamic WDM networks that gives accurate results in lower range computation time than previous models.

2. The second aim was the investigation of a suitable model for comparison of existing routing algorithms in the *data layer*. I have introduced traffic models and network extensions that made possible more realistic flow based studies of IP networks. The general conclusions made on the obtained results help in the development of new QoS routing schemes too.

3. The third objective focused on studies of the dynamic traffic grooming issue. The analysis of algorithms was performed with a network model that assumes the cooperation of the layers as well. I have analysed two scenarios that differed from the *data layer* traffic point of view. Networks with guaranteed bandwidth requests were considered first, and as second, networks with elastic traffic were investigated.

3 Methodology

The flavours of the different problems presented above can imply the use of different tools to be applied in the analysis. Let us give now a short summary of the available and applied methods.

The observation and the explanation of specific effects on network performance that stem from the choice of a *general* routing algorithm is more tractable if theoretical models are used. Applying queuing models in the field of telecommunication networks is almost obvious. A large population of independent users is assumed. The users want to transfer data using network resources and the population offers dynamically changing traffic. Stochastic theory allows the evaluation of the dynamic situations and the calculation of statistical behaviour of performance indices.

The first and a part of the third of my research objectives were approached with analytical models applying combinatorics, probability and queueing theory.

However, on the one hand, in many scenarios theoretical models fail due to long computation time, inaccuracy, need of too complex models or to the low robustness from the extension point of view. In these cases simulation can be applied that allows easier realisation of new routing algorithms and other schemes.

Although the evaluation time is sometimes long, the functionality and specific effects of the *general* routing solutions can be observed and controlled directly.

The accuracy of the results obtained with theoretical models can be evaluated by comparing it with simulation and I used this validation method also for my models.

In the case of my second and third objectives I implemented the needed functions in a suitable tool and evaluated the performance of the observed algorithms with simulation.

4 New results

4.1 Studies at the *optical layer*

The analysis of WDM networks that support dynamic reconfiguration and treat dynamically arriving optical channel requests has similar aspects but is not identical to the analysis of a simple circuit switched network. On the one hand, in the case of an optical network the route selection can be strongly influenced by the wavelength conversion capabilities of the nodes. On the other hand we cannot assume the arrival process of optical channel requests to be of the same characteristics as that of PSTN networks, i.e., it can not be modelled using a Poisson arrival process [12].

Several previous works were presented in recent years on parts of the theoretical modelling problem of such networks, e.g., [13, 14, 15]. Nearly all published models consider only Poisson traffic and the multifiber environment, i.e., the option to have more fibers per optical link, is introduced only in few of them. The model MLLC that was presented in [4] allows this option, but it still has somewhat drawbacks.

THESES I. ([C3, C5]) *I have constructed a theoretical model for the investigation of dynamic WDM network performance and analysed its complexity and accuracy.*

The model presented in [15] calculates effectively the connection request blocking and considers the above mentioned issues, i.e., the restricted capability of wavelength conversion and the special arrival processes of the optical connection requests. However, it ignores the multifiber option. I have extended this model and I have given a more general solution in [C3].

THESIS I.1. *I have developed WDMM, a model for blocking probability calculation in all-optical networks. It handles dynamically arriving connection requests, considers wavelength continuity constraints in the nodes and allows several fibers on the optical links, i.e., a multifiber network.*

The analysis is performed by an iterative algorithm equipped with a feedback on the non-blocked load. It calculates the occupancy of the particular routes by considering the constraints of connecting wavelength trunks. A wavelength trunk on a link is the set of optical channels that can be converted from one to the other. The model considers in each network node optical switching devices with either full wavelength conversion capability, or with limited-range converters or without converters. The computation is based on the following steps:

1. Initialise the input values,
2. compute link loads considering the blocking originating from other links,
3. calculate the probability that a set of wavelengths is occupied on a link,
4. extend the analysis to whole routes using an iterative method considering the mutual impact of adjacent links,
5. calculate total network blocking probability considering the offered traffic pattern,
6. if the required precision is reached then stop, else start again from step 2.

THESIS I.2. *I have given the complexity of WDMM and I have compared the model to the MLLC model from usability, complexity and accuracy point of view. I have shown the advantages of WDMM in different network scenarios.*

The calculation complexity of the WDMM model is $O(JC^3M)+O(JC^2M^2)+O(J^2M^2)$ in each step of the iteration where J is the number of links, C is the number of wavelengths and M is the maximum number of fibers per link. Although its complexity is significant, we find WDMM faster than the recursive solution of MLLC that is of $O(HC^5M^3)$ complexity.

The accuracy of the model was analysed for both regular (ring) and irregular (mesh) network topologies and with both uniform and non-uniform traffic patterns. Figure 1 presents illustrative results obtained with a 13 node uniform ring, where optical links contain 1 fiber and each fiber works with 24 wavelengths.

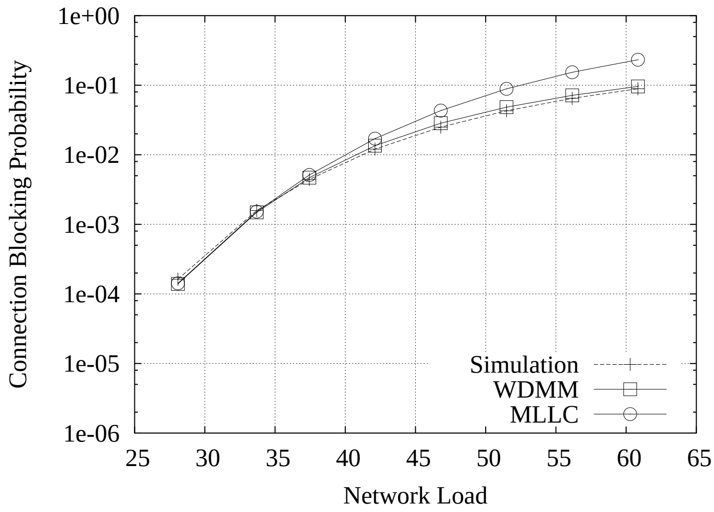

Figure 1: Blocking probability in the uniform 13-node ring

4.2 Evaluation of performance of the *data layer*

Many references address the analysis of QoS routing algorithms in the Internet, e.g, [6, 7, 8, 16]. However, most of these works assume flow based models representing the traffic via dynamically arriving requests, but with constant and fixed requirements, i.e., like circuit switched connections. In the *data layer* these classic approaches of traffic modelling fail to capture both the complex interactions of flows traversing multiple bottlenecks and common user behaviours.

Considering that QoS traffic in the Internet is mostly carried over TCP, an elastic traffic model can be assumed. Adaptivity is embedded in the congestion control algorithm of the TCP protocol which is a closed-loop protocol with implicit feedback from the network.

THESES II. ([J3, C4, C6, C7, C8]) *To evaluate routing performance I have introduced two flow level approaches to model the elastic traffic. I have formalised the routing problem considering outdated link state information and I have developed new routing strategies.*

The performance provided by a routing solution is strongly influenced by the elastic behaviour of the IP data flows. This holds particulary for the adaptive algorithms, i.e., for the case of QoS routing. To obtain more realistic results, more realistic models are required that consider special effects of the *data layer* traffic.

THESIS II.1. *I have introduced the Time-Based (*TB*) and the Data-Based (*DB*) models in the flow level performance analysis of IP traffic. I have defined the related performance measures and compared the two approaches. I have given a formulation of the routing problem and provided terms on previously introduced solutions.*

In the Time-Based (*TB*) model, flows are described by their duration (holding time), and by their bandwidth requirements. The effectiveness of this model is questionable if best-effort, data-based traffic is considered. Typically, if using a best effort service, the data-centric connections of IP adapt their sending rates to the current network congestion, which cannot be known a priori.

Indeed, the actual time required to successfully end the data transfer depends on many factors, and mainly from the varying assigned bandwidth while the connection is active. Thus, I have introduced the Data-Based (*DB*) traffic model, where the connection lasts until all the data amount S_D associated to the flow is transmitted. Figure 2 illustrates the main difference between *TB* and *DB* models.

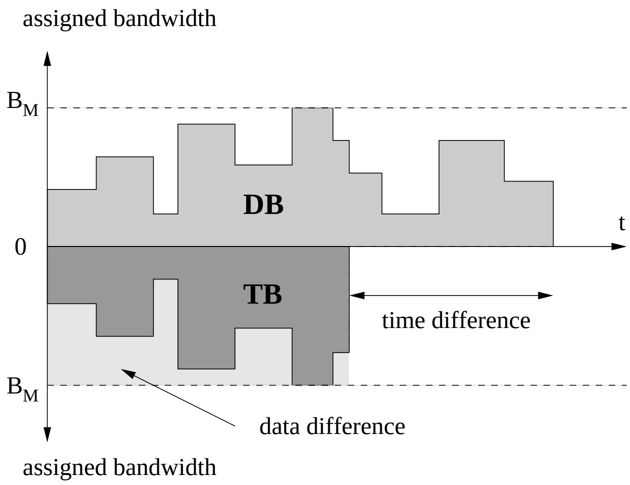

Figure 2: Traffic models *TB* and *DB*

I have included in both models the starvation effect: users abort the data transfer due to poor performance. It is modelled with the help of a threshold assigned to each flow that determines the acceptable value of the current transferring rate.

The starvation probability p_s becomes the other very relevant performance index beside the average bandwidth or throughput per flow named T. The latter is defined as the mean value of bandwidth that flows obtain during their lifetime, averaged among all the source-destination pairs, where only the flows that successfully complete the transfer are taken into account. In the Data-Based scenario, the performance can be characterised also by the dilatation factor D_f, i.e., the ratio between the completion time of a flow and its minimum completion time that can be derived from its predefined maximal bandwidth.

Analysing and comparing routing algorithms as *WS* [17], *MD* [6] or *LD* [18] also the relative gain of the average throughput η can be selected as performance index. It is obtained using the T values resulted by a QoS-aware routing algorithm with respect to those resulted by *Fixed Shortest Path*.

THESIS II.2. *I have extended the network model to consider outdated link information in route selection and investigated its effects on the network performance.*

Any distributed routing algorithm requires the exchange of information among nodes in order to compute the available routes and their current costs. The advantage of QoS routing is maximal when the routing algorithm exploits information on current utilisation of resources. This information, however, is prone to error measurements, and, most of all, it quickly becomes outdated. Indeed, stale load information on links can even lead to wrong routing decisions that can cause an avalanche effect forcing other route selections to choose the wrong paths.

I have considered a Timer Based Trigger information update protocol [16] and extended the network model implementing the versions of the routing algorithms that use stale information. The studies have been focused on the degradation of the performance induced by large update times, while the implementation details of the protocol were disregarded.

Several routing algorithms have been analysed with simulation. As it could be expected, on the one hand, the lower is the update frequency, the lower becomes the mean throughput of the connections that terminate ordinary. The gain of QoS algorithms in the low-load region vanishes almost completely if the update period t_u is comparable to connection duration. On the other hand, t_u does not affect strongly the starvation probability except for very large update periods.

THESIS II.3. *I have proposed the routing strategies realising Multimetric Sequential Filtering (*MSF*). The performance degradation due to large link state update periods can be avoided by using these algorithms.*

Considering the above results the goal of a new QoS algorithm is to be robust in two ways. Tolerance to high network loads and to link state information instability is required, while working with moderate computing complexity. I have developed a new set of algorithms that select the suitable route through a number of steps. At each step, the set of feasible paths is ordered according to a metric, and the paths in the bottom half of the ordered set are dropped.

Varying the number of steps and the metrics that are mostly recycled from previous QoS routings I have created four MSF algorithms. After the formulation their performance have been analysed in large update period scenarios and the results have been compared to those of known routing algorithms.

Figure 3 shows some illustrative results obtained with a mesh topology network. The reported *MSF* algorithms inherently lessen the impact of outdated information by restricting their scope to a limited set of paths, namely those with smaller hop count and larger capacity. Similarly to the algorithm *LD*, MSF3 and MSF4 include the load dependent option [18], i.e., congestion on network resources affect the choice of the route. Unless *LD* and *WS*, the *MSF* algorithms do not loose to much of their performance and do not perform worse than *FSP* even if the information are stale.

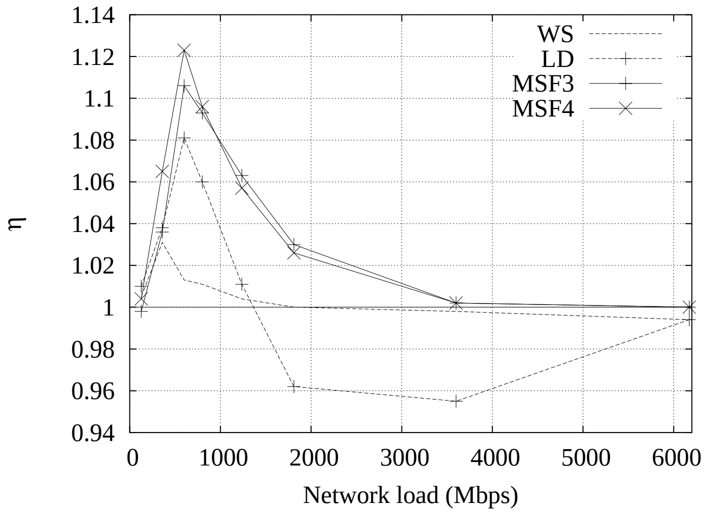

Figure 3: Relative gain η for 100 s update period

THESIS II.4. *I have developed the Network Graph Reduction technique that implicitly allows to avoid the congested resources of the network. The investigations show that routing algorithms realising this technique perform better than the classical ones.*

The conditional decision in the load dependent routing methods, e.g. *LD* tries to model a choice of route that is dependent on network load: when the network seems to be overloaded, the algorithm chooses the *FSP*. Since the network load is typically not known to the routing algorithm, not even in the case of centralised schemes, the identification of the high load zone remains the main problem.

To eliminate these problems, I have proposed a routing algorithm using a slightly modified perspective. Earlier QoS routing algorithms perform a choice of a suitable path considering a series of $c^{\gamma}(\cdot)$ cost function. Now, instead of trying to find new and cute adaptive cost metrics, the same metric that works well for light loads can be applied at high loads. The only difference is the use of a *reduced graph* that contains only uncongested links, i.e., links whose load is under a given threshold.

A drawback of this rather simple modification of, for instance, the *MD* and *WS* routing is an implementation issue. Unfortunately, if the *NGR* methodology is combined with some algorithms, the hop-by-hop implementation property is not preserved. However, when the original algorithm can be implemented in a hop-by-hop manner, also a hop-by-hop version *NGR HbH* can be defined. In this case every node implements its own locally-optimal version of the algorithm.

I have analysed the performance of the *NGR* algorithms comparing them with the classical QoS solutions in both stationary and variable traffic pattern scenarios. Figure 4 presents some results obtained in a random generated mesh topology network.

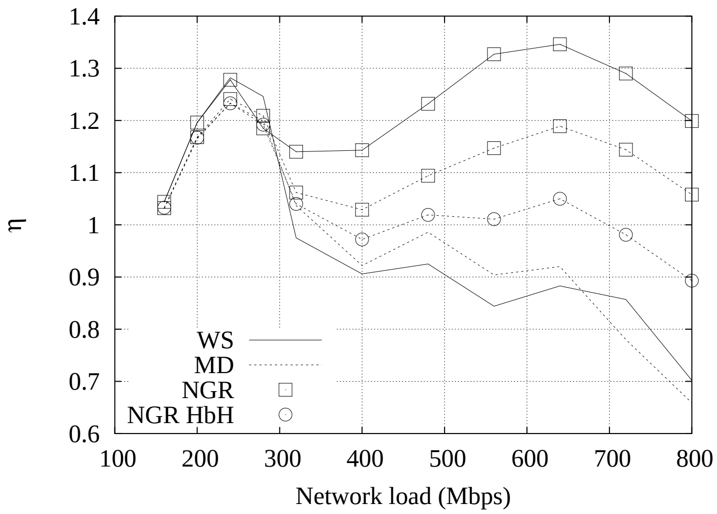

Figure 4: Relative gain η with stationary traffic

The advantage of QoS routing algorithms over *FSP* at low load is clear, but while the classic *MD* and *WS* implementations fall below the *FSP* at high load, *NGR* algorithms always remains above *FSP*. The hop-by-hop implemented version *NGR HbH* features a performance midway between the *consistent* version of *NGR* and the classic algorithms. The results confirm that locally-optimal decisions limit the benefits of the *NGR* approach.

4.3 Dynamic grooming analysis

Separating the layers of IP over WDM networks simplified models can be applied in the investigation. However, the issues concerning the interaction of the *data layer* and the *optical layer* can not be neglected. The aim of this cooperation is the effective usage of network resources in both layers.

The *grooming* mechanism that captures the problem of sharing optical channels among user traffic of much lower data rate is widely applied in statically configured optical networks. In recent years, using the on-demand switched WDM networks many dynamic solutions were proposed and analysed as well [9, 10, 11, 19]. On the one hand, the main issue of dynamic grooming is strongly connected to the routing in the *data layer*, since thereby the optical channel used for the transmission of user data will be selected. On the other hand, the performance of the routing can be enhanced if the virtual topology, i.e., the set of the established *lightpaths* is suited well to the network traffic.

THESES III. ([J1, J2, C1, C2]) *I have extended the network model and I have investigated IP over WDM networks using dynamic grooming.*

First, I have studied scenarios where CBR flow requests arrive to the *data layer*. Under certain conditions the model that was created for the analysis of the *optical layer* can be extended for this case of guaranteed bandwidth traffic.

THESIS III.1. *I have proposed the theoretical model HGGM for the calculation of blocking in IP over WDM networks with dynamic grooming and guaranteed bandwidth requests.*

Allowing time division multiplexing (TDM) on the optical channels, we can define *subwave channels* that can be switched by reordering the timeslots at the nodes. Network nodes are assumed to be homogenous from the point of view of the wavelength conversion and the timeslot reordering capability. A *subwave channel* trunk is defined as a set of those channels on a link, that can be converted one to the other in the nodes. Depending on the capabilities of the nodes, there can be more *subwave channel* trunk on an optical link.

In this scenario connection based communication is considered in the *data layer*. Each connection requires one end-to-end *subwave channel* to transfer its user data. The assumed grooming policy is of *peer* architecture, i.e., the decisions of the *general routing problem* are based on the information of both network layers.

Using the above assumptions the analysis of multifiber dynamic WDM networks based on the WDMM has been extended to the HGGM model. Due to the analogies of the wavelength trunk concept and of the *subwave channel* trunk concept the extension is feasible by redefining some parameters. With HGGM the blocking probability of user requests with guaranteed bandwidth can be calculated in a multifiber dynamic IP over WDM networks with TDM capabilities and allowing peer grooming.

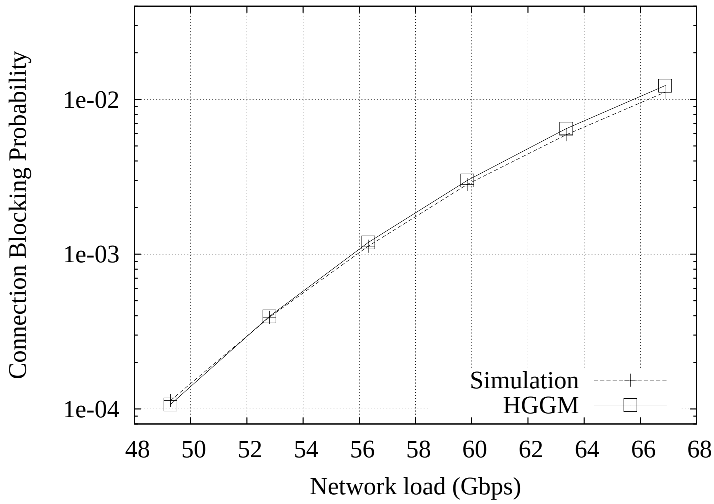

Figure 5: Blocking probability in the CWEN network

The model was tested on regular and irregular topologies with several traffic scenarios. It is not surprising, that the same conclusions can be given on the accuracy as for the WDMM. Figure 5 illustrates the high accuracy of HGGM. These results were obtained using a mesh topology with links of different capacity and 32 *subwave channel* trunks on each link.

THESIS III.2. *I have applied and compared the* TB *and* DB *traffic models in IP over WDM networks. I have identified the main performance measures and analysed them in scenarios with different dynamic grooming policies of overlay architecture.*

A more interesting problem is the analysis of the interaction in IP ambient, i.e., when *data layer* is modelled to catch the special characteristics of Internet traffic. As mentioned above, many papers were published on the grooming issue in IP over WDM networks. All these works, however, simply disregard the elastic nature of TCP/IP traffic. I have applied and compared the *TB* and *DB* traffic models in the performance analysis of the *data layer* using dynamic grooming.

In the multilayer network model, a path connecting two routers in the IP layer is called a *virtual* or logical path, because it is created over some established *lightpath* in the optical layer, i.e., over virtual links. Considering the structure of current networks the most feasible grooming architecture is the *overlay* one, which does not allow any direct interaction between the routing functions of the layers. The only, but not obvious function of grooming is to decide whether a new traffic relation must be routed at the IP level, i.e., using the current virtual topology or the setup of new virtual links is required.

I have adopted to the elastic traffic models and implemented the policies *Optical-level First* (*OptFirst*) and *Virtual-topology First* (*VirtFirst*), which were presented in [20] for CBR traffic. To achieve the proper function of the latter the definition of the parameter opening threshold th_o was required. To capture the characteristics of the grooming policies I have identified suitable performance measures in both the *optical* and *data layer*: average throughput per flow T, starvation probability p_s, average number of IP hops per flow N_l, average number of optical hops per *lightpath* N_{lo}, average number of the used optical channels per optical link $L_o$and the ratio between the opening rate of *lightpaths* and the arrival rate of flow requests R_o.

They were evaluated and analysed for regular and irregular topologies. As illustration, on Figure 6 the per flow throughput T was plotted using a mesh topology network. On the one hand, the difference in the performance results of the two traffic model approaches is striking here as well for both grooming policies. On the other hand, the difference in the handle of the current virtual topology resources at the grooming solutions *OptFirst* and *VirtFirst* imply large differences in the performance experimented by the users. However, to get a clear view on this issue also the other performance measures, e.g. $p_s$have to be considered.

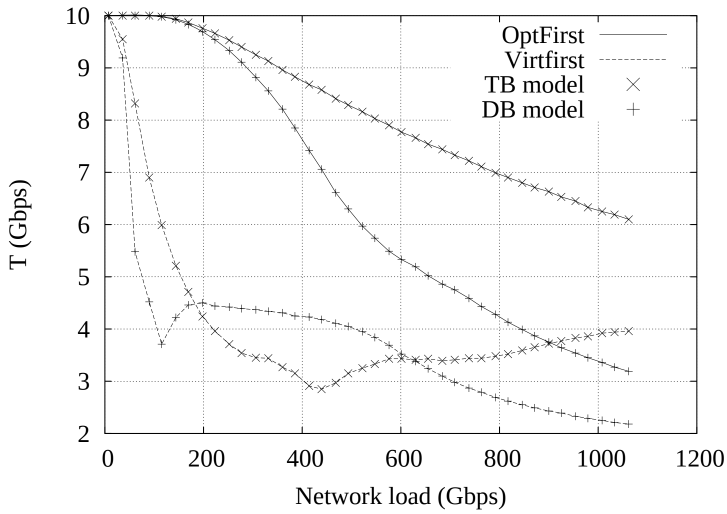

Figure 6: Average bandwidth per connection for *DB* and *TB* models using different grooming

5 Application of the results

On the one hand, the performance analysis of telecommunication networks helps to better understand the behaviour of the applied mechanisms. On the other hand, it can prepare the network planning task and the development of new solutions that may work more effectively.

The results presented in the dissertation concern the modelling and analysis problem of both the *optical layer* and the *data layer* in IP over WDM networks. The theoretical model of Theses I provides an effective method to calculate request blocking probability in WDM networks with dynamic switching capabilities. The models and algorithms of Theses II and Theses III are implemented in the GANCLES simulation tool [C1].

References

[1] B. Rajagopalan, J. Luciani, and D. Awduche. RFC 3717: IP over optical networks: A framework, March 2004.

[2] L. Li and A. K. Somani. Blocking performance analysis of fixed-paths least-congestion routing in multifiber wdm networks. In *Proc. of SPIE Photonics East'99*, pages 56–67, September 1999. Boston, MA USA.

[3] A. Birman. Computing approximate blocking probabilities for a class of all-optical networks. *IEEE Journal on Selected Areas in Communications*, 14(5):852–857, 1996.

[4] R. Srinivasan and A. K. Somani. A generalized framework for analyzing time-space switched optical networks. In *Proc. of IEEE INFOCOM'01*, April 2001. Anchorage, USA.

[5] S. Subramaniam, A. K. Somani, M. Azizoglu, and R. A. Barry. The benefits of wavelength conversion in wdm networks with non-poisson traffic. *IEEE Communications Letters*, 3(3):81–83, 1999.

[6] Q. Ma and P. Steenkiste. Routing traffic with quality-of-service guarantees in integrated services networks. In *Proc. of 8th IEEE/ACM International Workshop on Network and Operating Systems Support for Digital Audio and Video (NOSSDAV 1998)*, July 1998. England.

[7] D. Cavendish and M. Gerla. Internet qos routing using the bellman-ford algorithm. In *Proc. of IFIP Conference on High Performance Networking, HPN 1998*, 1998. Vienna, Austria.

[8] G. Apostolopoulos, D. Williams, S. Kamat, R. Guerin, A. Orda, and T. Przygienda. RFC 2676: QoS routing mechanisms and OSPF extensions, August 1999.

[9] R. Dutta and G. N. Rouskas. Traffic grooming in wdm networks: past and future. *IEEE Network Magazine*, 16(6):46–56, 2002.

[10] X. Zhang and C. Qiao. An effective and comprehensive approach to traffic grooming and wavelength assignment in sonet/wdm rings. *IEEE/ACM Transactions on Networking*, 8(5):608–617, 2000.

[11] H. Zhu, H. Zang, K.Zhu, and B. Mukherjee. A novel generic graph model for traffic grooming in heterogeneous wdm mesh networks. *IEEE/ACM Transactions on Networking*, 11(2):285–299, 2003.

[12] et al. Kaminow, I. P. A wideband all-optical wdm network. *IEEE Journal on Selected Areas in Communications*, 14(5):780–799, 1996.

[13] A. Mokhtar and M. Azizoglu. Adaptive wavelength routing in all-optical networks. *IEEE/ACM Transactions on Networking*, 6(2):197–206, 1998.

[14] Y. Zhu, G. Rouskas, and H. Perros. A path decomposition approach for computing blocking probabilities in wavelength routing networks. *IEEE/ACM Transactions on Networking*, 8(6):747–762, 2000.

[15] A. Sridharan and K. N. Sivarajan. Blocking in all-optical networks. In *Proc. of IEEE INFOCOM'00*, March 2000. Tel-Aviv, Israel.

[16] G. Apostolopoulos, R. Guérin, S. Kamat, and S. K. Tripathi. Quality of service based routing: A performance perspective. In *Proc. of ACM SIGCOMM'98*, 1998. Vancouver, Canada.

[17] Z. Wang and J. Crowcroft. Qos routing for supporting resource reservation. *IEEE Journal on Selected Areas in Communications*, 14(7):1288–1294, 1996.

[18] C. Casetti, G. Favalessa, M. Mellia, and M. M. Munafò. An adaptive routing algorithm for best-effort traffic in integrated-services networks. In *Proc. of 16th International Teletraffic Congress, IEE ITC-16*, June 1999. Edinburgh, UK.

[19] K. Zhu and B. Mukherjee. Traffic grooming in an optical wdm mesh network. *IEEE Journal on Selected Areas in Communications*, 20(1):122–133, 2003.

[20] X. Niu, W. D. Zhong, G. Shen, and T. H. Cheng. Connection establishment of label switched paths in ip/mpls over optical networks. *Photonic Network Communications*, 6(1):33–41, 2003.

Publications

Journals

[J1] R. Lo Cigno, E. Salvadori, and Z. Zsóka. Dynamic Grooming in IP over Optical Networks based on the Overlay Architecture. *Optical Switching and Networking*, 3(2):118–133, 2006.

[J2] Zoltán Zsóka. Dinamikus forgalomkötegelés (grooming) analízise optikai hálózatokban. *Magyar Távközlés*, 15(2):33–37, 2004.

[J3] C. Casetti, R. Lo Cigno, M. Mellia, M. M. Munafó, and Zoltán Zsóka. A new class of qos routing strategies based on network graph reduction. *Computer Networks*, 41(4):475–487, 2003.

Conferences and workshops

[C1] R. Lo Cigno, E. Salvadori, and Z. Zsóka. Dynamic grooming in overlay networks: A study with realistic traffic based on Gancles simulation package. In *Proc. of 9th IFIP TC6 Conference on Optical Network Design and Modelling, ONDM 2005*, February 7-9 2005. Milano, Italy.

[C2] R. Lo Cigno, E. Salvadori, and Z. Zsóka. Elastic traffic effects on wdm dynamic grooming algorithms. In *Proc. of IEEE GLOBECOM'04*, Nov. 29 - Dec. 3 2004. Dallas, Texas USA.

[C3] Zoltán Zsóka. Blocking probability of all-optical multifiber networks. In *Proc. of 7th IFIP Working Conference on Optical Network Design and Modelling, ONDM 2003*, February 3-5 2003. Budapest, Hungary.

[C4] C. Casetti, R. Lo Cigno, M. Mellia, M. M. Munafó, and Zoltán Zsóka. A new class of qos routing strategies based on network graph reduction. In *Proc. of IEEE INFOCOM'02*, June 23-27 2002. New York, NY USA.

[C5] Zoltán Zsóka. Ason hálózatok forgalmának modellezése. In *Proc. of HTE-BME 2002 diákkonferencia*, May 2002. Budapest, Hungary.

[C6] C. Casetti, R. Lo Cigno, M. Mellia, M. M. Munafó, and Zoltán Zsóka. A realistic model to evaluate routing algorithms in the internet. In *Proc. of IEEE GLOBECOM'01*, Nov. 25-29 2001. San Antonio, Texas USA.

[C7] C. Casetti, R. Lo Cigno, M. Mellia, M. M. Munafó, and Zoltán Zsóka. Routing algorithms evaluation for elastic traffic. In *Proc. of IEEE Workshop on High Performance Switching and Routing, HPSR 2001*, May 29-31 2001. Dallas, Texas USA.

[C8] C. Casetti, R. Lo Cigno, M. Mellia, M. M. Munafó, and Zoltán Zsóka. Qos routing strategies when link state information is out-of-date. In *Proc. of 8th IFIP Workshop on Performance Modelling and Evaluation of ATM and IP Networks*, July 17-19 2000. Ilkley, West Yorkshire U.K.

List of Acronyms

ASON	Automatic Switched Optical Network
CBR	Constant BitRate traffic
DB	Data-Based traffic model
FSP	Fixed Shortest Path routing
G-OXC	Grooming OXC
HGGM	Homogenous Guaranteed-traffic Grooming Model
IP	Internet Protocol (Network)
LD	Load Dependent routing
MD	Minimum Distance routing
MLLC	Multifiber Link-Load Correlation
MSF	Multimetric Sequential Filtering
NGR	Network Graph Reduction
OADM	Optical Add-Drop Multiplexer
OXC	Optical Crossconnect
QoS	Quality of Service
ROADM	Reconfigurable Optical Add-Drop Multiplexer
TB	Time-Based traffic model
TCP	Transmission Control Protocol
WDM	Wavelength Division Multiplexing
WDMM	Wavelength Dependent Multifiber Model
WS	Widest-Shortest routing