Traffic Engineering in Case of Interconnected and Integrated Layers

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***Abstract*—In this paper, we compare two routing scenarios for grooming-capable optical-beared two-layer networks that are capable of meeting the Traffic Engineering (TE) objectives. The first one applies completely dynamic WDM layer that adapts instantly to all traffic changes. The second one is based on fixed WDM topology ("lower layer"). To achieve the best performance, the fixed lightpath system is optimized in advance according to the characteristics of the expected traffic. In both cases, the upper layer is assumed to be dynamic. We perform extensive simulations to compare these two multi-layer Routing and Traffic Engineering approaches that are currently both of particular practical interest with their inherent advantages and drawbacks.**

I. Introduction

Networks, particularly in the metro and backbone part, consist typically of two or more layers, where each layer employs a different network technology. The lower layer is mostly either a dense or sparse Wavelength Division Multiplexing (WDM) layer. The connections of this layer are the lightpaths. The system of lightpaths provides the virtual (or logical) topology [1].

While the lower layer is an 'optical' one, the upper layer is typically an 'electronic' one capable of performing joint time and space switching, typically using a digital switch that can be an IP or MPLS router or an SDH digital cross-connect. The lower, 'optical' layer is seen by this upper 'electronic' layer as a given virtual topology. A lightpath of the lower layer corresponds to a single link in the virtual topology. In other words, paths of the lower layer are seen as links of the upper layer, and as the traffic of this upper layer is routed over the virtual topology it is also "groomed" into the physical one wherever a lightpath is terminated, i.e., wherever an upper layer node can be found [2].

There arises the question how can these layers be operated together. Both IETF and ITU-T propose models and solutions how to operate these two or more layers together [3] [4]. For simplicity reasons, from now on we will assume two layers only [5]. Here we will distinguish four different cases from the aspect of dynamics of the two layers.

1) The simplest approach is when both the layers are statically configured, i.e., however the traffic and network conditions change both the layers will be used as they are.
2) The more complex case is when the upper layer is dynamic, handled by the control plane, that reacts well to changing conditions and where user signalling is used to set up and tear down connections, while the lower layer is statically configured.
3) As the third case, we consider the scenario when the upper layer is fully dynamic, while the lower one can be reconfigured time to time. In this case, any change of lightpaths that carry any traffic will cause interrupt of that traffic. There are two options for the solution of this problem: First, to change only those lightpaths that do not carry any traffic; however, this situation may happen very rarely. Or second, to assume that the upper layer will restore the sessions in mili-seconds, so that the deterioration in the quality of service will be negligible. We have assumed this second approach, since the majority of transmissions relay on the TCP/IP transmission that will resend the few lost packets, and a data transfer, web browsing, downloading or some streaming media application will not be affected by these short interrupts. However, if there are some mission critical transmissions, they can be carried over un-interruptible lightpaths.
4) The fourth, most complex case is when both the layers are handled via a distributed control plane to ensure full and joint on-line adaptivity of both the layers. This approach has the highest capability of adapting to changing traffic and network conditions, however, it will cause the largest number of short interrupts due to the never ending reconfigurations.

For statically configured or periodically reconfigured systems, a management plane is sufficient. This is typically a centralized approach. Whenever we assume fully dynamic and adaptive approach, a control plane, with all its protocols for topology and link state discovery, connection set up and tear down, etc., is required to ensure distributed operation over up-to-date data.

In this paper, we compare case 3 to case 4, referring to case 3 as "Overlay" while to case 4 as "Integrated". In general, there are four different models defined by the IETF for vertical interoperation of the layers, or rather for the interoperation of the control planes of these layers [6].

When the layers are assumed to be operated by different providers, the control planes of these different layers exchange a certain amount of information over well defined interfaces, and the three models are referred to as vertical interconnection. The overlay model is the simplest, followed by the augmented one and by the peer one [7] [8]. In the overlay model a server client architecture can be recognized where the lower layer acts as a server for the upper, client layer. In the peer model, layers act as peers, i.e., they exchange all the necessary information so that any of them can initiate actions, e.g., a connection set-up, by using resources of both the layers.

A more flexible and somewhat simpler is the fourth approach the vertically integrated model, when it is assumed, that all the layers are operated by the same provider, i.e., all the information and all the resources are available without complex interfaces and without sharing responsibilities.

Assuming the above models we investigate how can the Traffic Engineering objectives be achieved in such a multi-layer networks. In Section II and III, the previously introduced models are described in details. In Section IV, comparative simulations are shown and discussed.

II. Traffic Engineering With Adaptive WDM Topology

By using dynamic optical layer, it is possible to create adaptive set of lightpaths that satisfies emerging traffic demands. Lightpaths are special routes: they arise and terminate in the electronical layer, however they do not pass over it elsewhere. In the WDM layer, a lightpath connects two physically adjacent or distant nodes. These two physical nodes is seen as adjacent by the upper layer.

Multiplexing and demultiplexing the traffic of a lightpath cannot be solved currently by applying only optical devices. In these cases lightpaths have to be torn down, their traffic has to be taken up to the electronic layer that increases the number of lightpaths. This operation needs opto-electronic converters to be reserved. Their number is limited per node.

Our model is dynamic: we assume demands arriving one-by-one (Discrete Event Simulation) [9]. Demand will be routed on arrival on free or sharable resources. We assume that demands arriving to the WDM layer are results of some routing mechanism in the upper, electronic layer.

Routing demands on exclusive lightpaths is quite a resource wasting solution since capacity of a single wavelength channel is much larger than the typical bandwidth of traffic demands. Therefore we apply grooming to bundle traffic of different demands together in one lightpath. However if already existing lightpaths are only combined to create routes for traffic demands, network resource usage will increase highly since demands are routed on de-tours [10]. Therefore in certain circumstances we allow fragmenting lightpaths to add or drop some of their demands. However this means reserving more opto-electronic converters that makes the solution more expensive, causes traffic loss during realizing fragmentation and the carried traffic will be delayed because of passing over the electronic layer.

The aim is to create a reasonable, feasible and inexpensive lightpath set: as few network resources (wavelength channels and opto-electronic converters) have to be reserved as possible to accommodate the offered traffic.

If a new demand arrives at the network, the following actions may happen.

1) Its traffic is groomed together with the traffic of already existing lightpaths. In this case, lightpaths will carry more traffic.
2) New lightpaths are created.
3) Existing lightpaths are fragmented to multiplex/demultiplex the traffic of the new demand at a certain node. This is a subcase of action 1. It can happen but it is not necessary to apply.

These cases can be combined as well. It can happen that a new demand will be routed on some existing lightpaths, some of them will be fragmented, and even new lightpaths will be created.

A. Wavelength Graph

As can be seen above, we need a network model representing not only different wavelengths but inner structure of network nodes as well, to be able to keep the introduced constraints. We apply the so called Wavelength Graph model. This model was first proposed in [11]. Wavelength graph can be derived from the real physical network. The topology is the same, however appearance of network nodes and network links is special. In a wavelength graph, network nodes are modelled by subgraphs. Topologies of these subgraphs are based on the function of the modeled network node. In our case, it is important to avoid disallowed routes, e.g., it has to be assured that no algorithm can create a lightpath applying different incoming and outgoing wavelengths in a node.

Network links are modeled by as many graph edges as the number of wavelengths that can be utilized in the fiber. The cost of the edges in a wavelength graph are based on their functionality and on our aims. For details see Section II-B.

We will refer to the simulator applying the introduced wavelength graph model as Wavelength Graph Tool (WGT).

B. Routing traffic demands

Assuming dynamic WDM layer means that no constant lightpath set is designed neither in advance, nor periodically. Lightpaths are added/dropped/fragmented/concatenated dynamically based on traffic demands appearing/expiring in the upper layer. Therefore, demands are not routed strictly on the already existing lightpath set. Instead, the common Control Plane investigates how the lightpath set should be modified in order to serve the recently arrived demand the most economical and efficient way.

The advantage of this method is that lightpath set is exploited as far as possible. Additionally, a demand is not refused until there is available resources in the network. However, the disadvantage of the method is that frequent

Transition	Cost
Edges modeling a single λ in a fiber carrying traffic	1
Edges modeling a single λ in a fiber without traffic	25
Edges modeling transition between elctronic and optical layer carrying traffic	250
Edges modeling transition between elctronic and optical layer without traffic	50
Edges modeling fragmenting of existing λ-paths	500

TABLE I
COSTS APPLIED IN DYNAMIC WDM LAYER WHILE ROUTING TRAFFIC DEMANDS

fragmenting/concatenating of lightpaths causes delay of the traffic or even traffic loss. Therefore, weights of wavelength graph have to be set; so that traffic grooming is preferred against lightpath fragmentation.

By using a well-constructed cost-function fragmentation and hereby opto-electronic conversion will be applied as few times as possible, and lightpaths will be as highly utilized as possible.

Costs applied in wavelength graphs in case of adaptive WDM topology are presented in Table I.

As can be seen it is always preferred to use already existing lightpaths. Termination of lightpaths is expensive to keep traffic in the optical layer as far as it is possible. The highest cost belongs to fragmentation of existing lightpaths.

By maintaining the costs described above any shortest path algorithm can be applied to accomodate the arrived traffic demands on existing/new/fragmented lightpaths. The found route in the wavelength graph will determine the tasks to do with lightpath set (resource reservation, fragmentation).

III. MPLS TRAFFIC ENGINEERING ON FIXED WDM TOPOLOGY

If statistical information on the network traffic is available, then it is possible to design a fixed WDM layer logical topology that maximizes the total throughput according to the expected traffic values. This approach has the advantage that the traffic flows are not disrupted by the logical topology reconfigurations and the required signaling complexity is less. In this study, a traffic pattern is used which changes with the time of the day. The expected values of the traffic bandwidths between every source destination pair in each hour is assumed to be available beforehand in the form of a traffic matrix. In the proposed TE strategy, a fixed WDM layer logical topology is designed using the traffic expectation information and to further reduce the blocking as the actual traffic values deviate from the expectations, the traffic flows are rerouted on the fixed logical topology. This strategy is composed of two phases: the first phase is the design of the WDM layer logical topology, the second is online rerouting of the LSPs.

A. Fixed WDM Logical Topology Design

This phase of the strategy is run offline. The aim is to design a fixed WDM logical topology that maximizes the amount of routed traffic over all hours of the given traffic matrix and satisfying the constraints on the utilized network resources. This problem is referred as Multi-Hour Virtual Topology Design problem in the literature [12].

The solution to this problem is produced by a Logical Topology Design Tool (LTDT) that uses a heuristic search algorithm and applies Tabu Search meta-heuristic on top of it. The traffic information is given in the form of a three dimensional array. The maximum expected traffic bandwidth between nodes i and j during hour h is denoted by $T_{i,j,h}$. The constraint on the network resources is the number of lightpaths in the topology to be generated and it is determined according to the amount of traffic in the traffic matrix. The algorithm starts with generating a random topology and improves that topology by changing the places of the lightpaths in the network. The objective criterion is the amount of routed traffic over all hours. A move is defined as closing a lightpath and setting up a new one. At each iteration, all the possible moves are calculated and the one giving the maximum objective value is chosen. To differentiate the moves giving the same objective value, a tie-breaker function is used.The tie breaker parameter is calculated as $\sum_{i,j \in V} \sum_{h=1}^{H} s_{ij} T_{i,j,h}$ where V is the set of nodes and s_{ij} denotes the number of hops on the shortest path between i and j in the resulting topology. Between moves giving the same objective value, the one with the smaller tie breaker value is chosen. The performance of this algorithm is investigated by comparing with the ILP solutions of the relaxed problem in [13].

The establishment and tearing down of the lightpaths in the physical layer is achieved by communicating with Wavelength Graph Tool (WGT). This scheme represents an example of the overlay model. WGT acts as the control plane for the WDM layer and sets up and tears down the lightpaths as requested by LTDT. If a lightpath establishment request cannot be satisfied, WGT informs LTDT and LTDT searches for the next move giving the maximum objective value and requests establishment and tearing down of the lightpaths corresponding to that move. After a number of unsuccessful tries, LTDT decreases the number of lightpaths and tries to generate a new topology.

B. Dynamic LSP Rerouting

As explained in the first phase, the virtual topology is designed based on the traffic expectation information. However, that kind of statistical traffic information is not exact in general and the actual traffic can significantly deviate from the expected value. To improve the blocking performance of the network in such cases, a dynamic online TE scheme is developed. This TE scheme optimizes the network by rerouting the LSPs on predefined paths. Using the make before break feature supported by MPLS, the LSPs can be rerouted without disrupting the traffic flows.

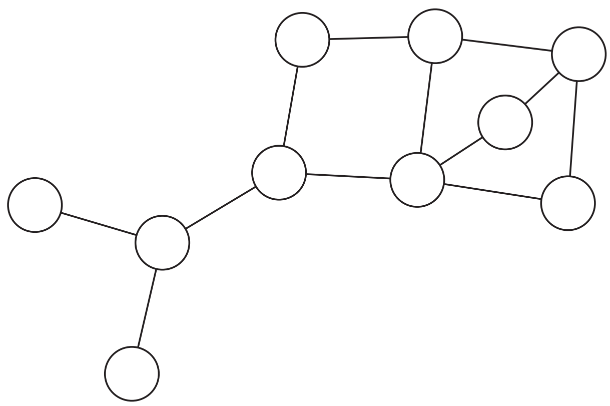

Fig. 1. Topology of underlying physical network

Rerouting is done using an alternate routing algorithm. On the fixed WDM logical topology designed in the first phase, for each source destination pair, a number of shortest paths are calculated. The LSPs are rerouted along paths that are chosen among these paths between the source and destination nodes. To choose the best path, a dynamic cost function is utilized which depends on the available capacity along the routes and the length of the route. The cost function for path p, is given by:

$$F_{\text{cost}}(p) = L_p + A^{u - \frac{C^p_{\text{residual}}}{C}} \tag{1}$$

where, L_p is the number of hops on path p and C^p_{residual} is the residual capacity of the path after the LSP is routed along that path and C is the lightpath capacity. *A* and *u* are cost function parameters and the algorithm gives the best results with the values of 10 and 0.5 for *A* and *u* respectively [13]. If the available capacity along the path is not sufficient to route the demand, the path is given a predefined very high cost which is guaranteed to be higher than the cost of any path with sufficient available capacity. If there is no path with sufficient available capacity, then the path with the largest available capacity is chosen.

The utilized cost function favors the shorter paths when the network is lightly loaded. When the network is heavily loaded, the residual capacity becomes the dominant factor and the paths with higher residual capacity are more likely to be chosen.

IV. Simulations

The performances of the two TE approaches under the same traffic are investigated by simulations. The underlying physical network has 11 nodes and 12 links with two fibers at each link in the opposite directions (Fig.1).

The traffic is modeled in the level of LSP flows. The bandwidth of the traffic flow between each source destination pair has two components: the expected value and a Gaussian noise introduced to reflect the deviations from the expected bandwidth value.

To generate the expected traffic, a 24 hour traffic pattern is used the details of which are described in [13]. The standard deviation of the introduced noise is 0.1 times the expected bandwidth value. The actual traffic between nodes i and j at time t is calculated as

$$T_{act}(i,j,t) = T_{exp}(i,j,t) + N(0, (0.1 \times T_{exp}(i,j,t))^2) \tag{2}$$

A single LSP is established for each source destination pair using resource reservation. The changes in the traffic flows are modeled by updating the bandwidth requirements of the LSPs. The bandwidth updates arrive according to a Poisson process with rate $\lambda = 30$ arrivals per hour, and the update times belonging to each LSP are independent.

In the fixed topology MPLS TE approach, when a bandwidth update request arrives for an LSP flow, the best path is chosen among the precalculated paths between the source and destination nodes. Then, the LSP is rerouted along the chosen path with the new bandwidth. In the Adaptive Topology TE approach, the arrival of a bandwidth update request is treated as departure of the current LSP and arrival of a new one at the same instance with the new bandwidth requirement. In both of the approaches, if the requested bandwidth cannot be satisfied, LSP's bandwidth is not changed and the transcending part of the demand is lost.

The ratio of the maximum amount of traffic flow to the capacity of a single lightpath is referred as the *traffic magnitude*. The loss and resource usage performances of the TE approaches are investigated versus the traffic magnitude for various numbers of wavelengths per fiber.

The blocking performance and resource usage of both TE strategies are evaluated both individually and comparatively by simulations carried out with the same traffic demands for each strategy.

A. Analysis of the Adaptive WDM Layer

1) Reserved resources: Since fragmenting lightpaths is expensive, it should be avoided as much as possible. As long as there is enough wavelength to accommodate traffic on exclusive lightpaths, no fragmentation will happen. That is why we have the fewest and longest lightpaths, causing maximum wavelength resource usage when we apply the most wavelengths and offer the smallest traffic to serve (Fig.2(a) and Fig.3(a)).

If the same traffic level should be served on fewer wavelengths, or when increasing traffic level have to be accommodated on the same number of wavelengths, the average amount of traffic to be served per wavelength increases. In that case, lightpaths have to be fragmented. Fragmenting lightpaths results in more and shorter lightpaths than before as can be seen on Fig.2(a) and Fig.3(a). However since fragments of the cut lightpath are better utilized, this results in less total wavelength reserved in fibers. This quantity can be calculated by creating the product of average lightpath length and the number of lightpaths. It will be referred to as the wavelength resource usage on Fig.4(a).

Fragmentation is limited by the number of wavelengths, by the capacity of wavelength channels and even by arriving demands: if a traffic demand could be routed only through bottlenecks of the network, fragmentation and grooming do not help, the demand has to be blocked. Therefore, increase of traffic per wavelength cannot be fully managed by fragmenting lightpaths, thus wavelength resource usage cannot reach 100% and traffic loss will rise (Fig.6 and Fig.5(a)).

While Fig.3(a) shows that the higher traffic per wavelength definitely results in shorter lightpaths as explained above, according to Fig.2(a) if low number of wavelengths (4, 6) are operated in the network, number of lightpaths significantly decreases instead of increasing. In these cases, traffic loss is extremely high (Fig.5(a)), which means that the offered traffic load is much higher than the network capacity. Since this approach is an adaptive one, the high traffic loss means that the model attempted to utilize every possible spare capacity in the network. Therefore, as many traffic streams were groomed together as it was possible, lightpaths were fragmented almost in every node, that resulted in a large number of one-hop long lightpaths in the network. This is proved by the charts as well: in case of high traffic loss ratio (above 10%) average lightpath lengths is hardly more than one (Fig.3(a)), and the network utilization is very high (Fig.6)

For higher number of wavelengths (8, 12 and 16), the blocking ratio is much smaller, and the resource utilization ratio is lower (Fig.6). There are enough resources to route demands on exclusive lightpaths, as proved above.

2) Average λ-path configuration per hour: Fig.7 represents the number of average lightpath configuration changes per hour. If demands can be routed on exclusive lightpaths, no frequent re-configuration is needed, since fragmentation is rare. As traffic rate increases, more fragmentation have to be applied beside the same number of wavelengths.

If the network is full-fragmented, lightpaths are short, they are used by a large number of demands at the same time, and even later arriving demands will use them since lightpaths are nearly one hop long. In such circumstances, reconfiguration of lightpaths is quite rare as well.

Fig.7 shows that the fewest reconfiguration event belongs to the extreme cases mentioned above, while between them number of reconfiguration events is higher.

B. Analysis of MPLS TE on Fixed WDM Topology

Fig.5(b) shows that the traffic loss rate increases with the traffic magnitude and decreases with the number of lightpaths as expected. According to the results, 4 wavelengths represents a case where the network resources are insufficient to produce an acceptable loss performance even for smaller values of the traffic magnitude.

The numbers of lightpaths in the generated topologies are given in Fig.2(b). As mentioned in Section 2, the topology design algorithm makes use of traffic expectation information and determines the number of lightpaths to request according to the traffic rate. For higher values of the traffic magnitude, it requests to set up a larger number of lightpaths from the physical layer control plane. However, the number of lightpaths that can be established does not show a continuous increase with the traffic magnitude for all wavelength numbers. This is due to the limited physical layer resources. Fig.3(b) shows the average lightpath length in the established topologies. As it can be expected, average lightpath length exhibits a reverse behavior with the number of lightpaths, as the traffic magnitude increases. For the cases of 4, 6 and 8 wavelengths it can be seen that the bumps in the average lightpath length corresponds to dips in the number of established lightpaths and vice versa. For 12 and 16 wavelengths cases, the physical layer resources are more sufficient and increases in the average lightpath length does not have such a decreasing effect on the number of established lightpaths.

Fig.4(b) shows the total amount of wavelength resources utilized, which is calculated by taking the product of the number of lightpaths and average lightpath length. While these two parameters show the opposite behaviour, their product exhibits an increase with the traffic magnitude as far as the physical layer resources allow. For smaller numbers of wavelengths, total amount of utilized resources seems to stay around a constant value but for larger wavelength numbers, it shows an increase with the traffic magnitude.

C. Comparative Results

In Fig.8, the traffic loss ratio of the two TE approaches are compared for 4, 8 and 12 wavelengths. The traffic loss ratio of the Adaptive Topology approach is generally half a magnitude lower than the loss ratio of the Fixed Topology approach, as expected. When the current logical topology remains insufficient to satisfy the changing traffic demands by updating the electronic layer routes only, this approach can generate new routes by opening new lightpaths and adapting the topology according to the traffic. This improvement in the blocking ratio is at the expense of WDM topology reconfigurations with a frequency changing between 1.8 and 33 per hour, depending on the number of wavelengths and traffic magnitude. These reconfigurations may cause delay or extra traffic loss by interrupting the traffic flows passing through the reconfigured lightpaths.

The wavelength resource usages of the two approaches are given in Fig.9 for the same set of wavelength numbers. The Fixed Topology TE approach utilizes less wavelength resources than the Adaptive Topology approach. This is due to the fact that, the Adaptive Topology approach controls the electronic and optical layer jointly using full information of each layer. Knowing the topology and resource availability of the optical layer, it can arrange the electronic layer routes in a way to utilize more amount of optical layer resources in order to prevent blocking. While the difference between the resource usage ratios of both approaches is considerable for smaller numbers of wavelengths, it gets lower as the number of wavelengths increase. When more resources are available in the physical layer, the TE approaches can obtain more of the resources they need to satisfy the introduced traffic.

V. CONCLUSION

In this study, TE approaches are investigated in case of two different interoperation models for the optical and electronic layers. The first one is the integrated model where all layers are controlled by a distributed control plane and the second model investigated is the so-called overlay model. In the overlay model, the optical and electronic layers are controlled by separate control planes and limited amount of information is passed between them.

Both models have application scenarios they are suitable for. The integrated model is suitable for the scenarios where the network is operated by a single operator and the WDM layer is capable of performing fast reconfigurations which include set up and tear down of lightpaths dynamically. The second approach suits the case where limited amount of information exchange is allowed between the layers because of being operated by separate providers or network management purposes.

A traffic engineering approach with adaptive WDM topology is proposed for the integrated model. For the overlay model, a fixed WDM topology TE approach is used with dynamically changing electronic layer routes. The results demonstrate the benefits and drawbacks of both approaches. While Adaptive Topology approach better adapts to the traffic and has a lower traffic loss ratio, it utilizes more network resources. In addition, frequent WDM reconfigurations performed to prevent the blockings may decrease the throughput and cause disruption of the traffic flows and increase in the delay. The Fixed Topology approach has a worse blocking performance, however it also utilizes less network resources and do not disrupt the traffic flows. Its most important limitation is the need of prior information on the traffic expectation in order to be applied efficiently.

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REFERENCES

[1] B. Mukherjee, *"Optical Communication Networks"*, *McGraw-Hill*, New York, 1997.

[2] Arun Somani *"Survivability & Traffic Grooming in WDM Optical Networks"*, *Cambridge University Press*, ISBN-10: 0521853885, 2006

[3] Internet Engineering Task Force (IETF) *"Unique Features and Requirements for The Optical Layer Control Plane"* http://tools.ietf.org/html/draft-chiu-strand-unique-olcp-01

[4] International Telecommunication Union *"OTN - ITU-T Recommendations on ASTN/ASON Control Plane"*, http://www.itu.int/ITU-T/2001-2004/com15/otn/astn-control.html

[5] R. Sabella, H. Zhang, eds.: *Traffic Engineering in Optical Networks"*, *IEEE Network*, March/April 2003, Vol.17, No.2

[6] E. Dotaro, M. Vigoureux, D. Papadimitriou: *"Multi-Region Networks: Generalized Multi-Protocol Label Switching (GMPLS) as Enabler for Vertical Integration"*, Alcatel Technology White Paper, February 2005, researchlibrary.theserverside.net/detail/RES/1109006898_409.html

[7] B. Rajagopalan, J. Luciani, D. Awduche: *"Requirements for Traffic Engineering Over MPLS"*, Internet RFCs (2004).

[8] A. Rpdrigues-Moral, P. Binenfant, S. Baroni and R. Wu: *"Optical data networking: Protocols, technologies, and architectures for next generation optical transport networks and optical internetworks"*, IEEE/OSA J. Lightwave Tech., Vol.18, No.12, pp. 1855-1870, December 2000.

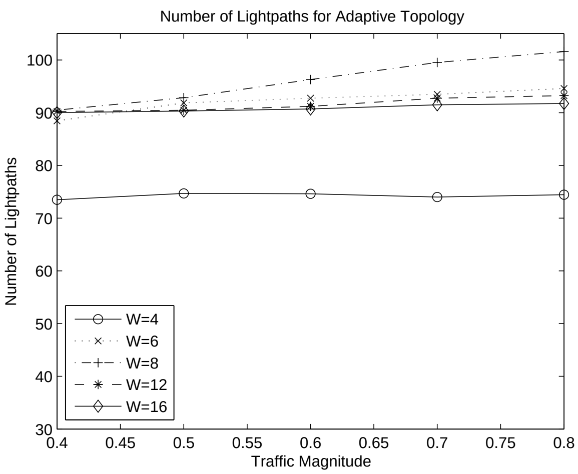
[9] Tibor Cinkler, Péter Hegyi, Géza Geleji, János Szigeti: *"Multi-Layer Traffic Engineering: Should Only the Upper-Most Layer be Switched?"*, ONDM 2006, 10th Conference on Optical Network Design and Modelling, Copenhagen, Denmark, May 2006.

[10] Cinkler Tibor, Hegyi Péter, Asztalos Márk, Geleji Géza, Kern András, Szigeti János *"Multi-Layer Traffic Engineering through Adaptive Lambda-path Fragmentation and De-Fragmentation: The Grooming-Graph and Shadow-Capacities"* Networking 2006, Coimbra, Portugal, May 2006.

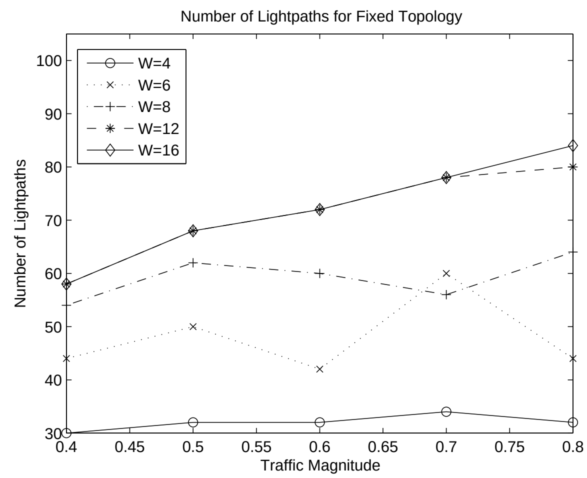
[11] T. Cinkler, R. Castro, S. Johansson: *"Configuration and Re-Configuration of WDM Networks"*, NOC'98, European Conference on Networks and Optical Communications, Manchester, UK, June 1998

[12] M. Pióro, D. Medhi: *"Routing, Flow, and Capacity Design in Communication and Computer Networks"*, Elsevier/Morgan Kaufmann Amsterdam, 2004.

[13] N. Sengezer, E. Karasan: *"An Efficient Virtual Topology Design and Traffic Engineering Scheme for IP/WDM Networks"*, in Proc. ONDM 2007, Athens, Greece, July 2007 .

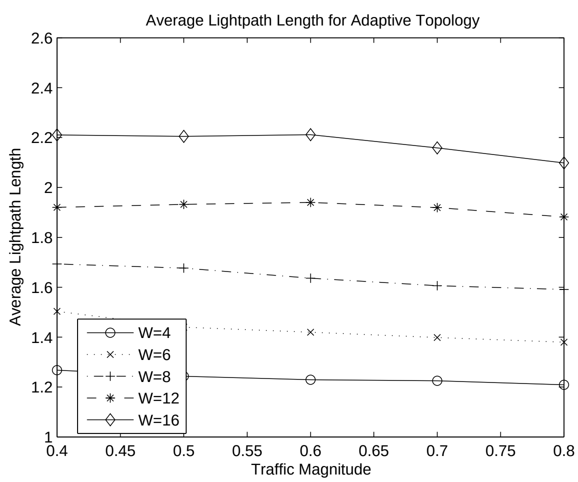


(a) on adaptive topology

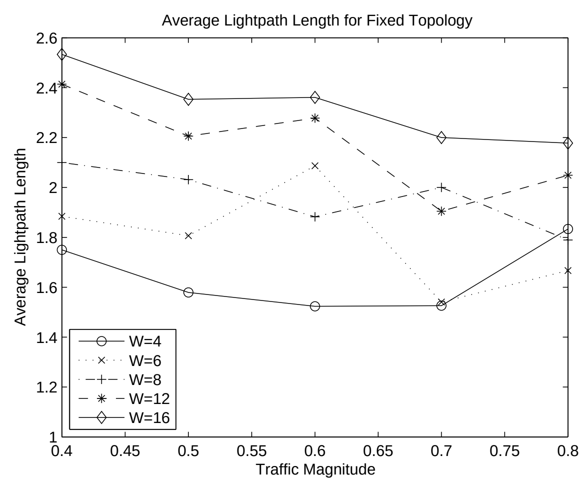


(b) on fixed topology

Fig. 2. Number of lightpaths

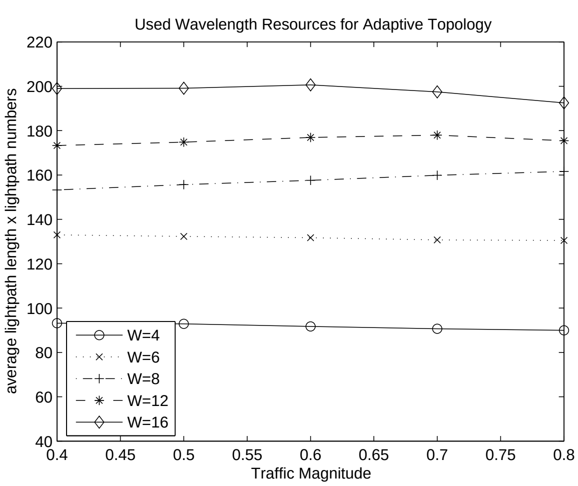


(a) on adaptive topology

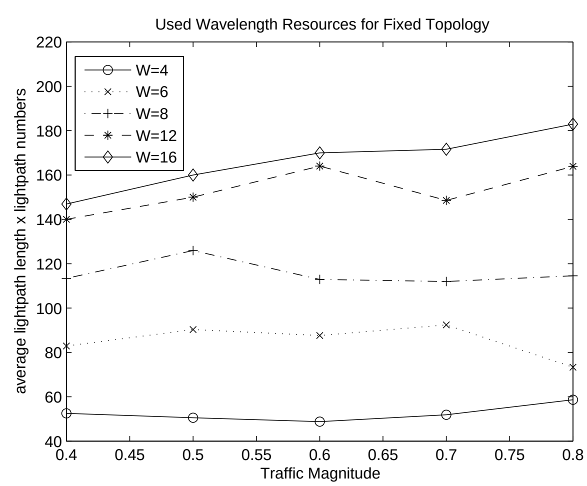


(b) on fixed topology

Fig. 3. Average lightpath lengths

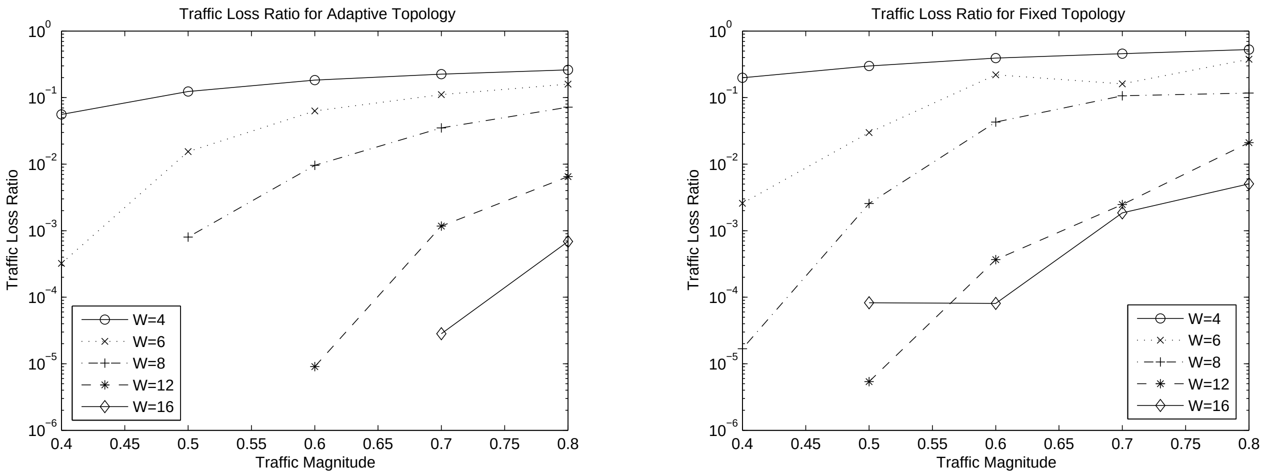


(a) on adaptive topology



(b) on fixed topology

Fig. 4. Utilized wavelength resources



(a) on adaptive topology

(b) on fixed topology

Fig. 5. Traffic losses

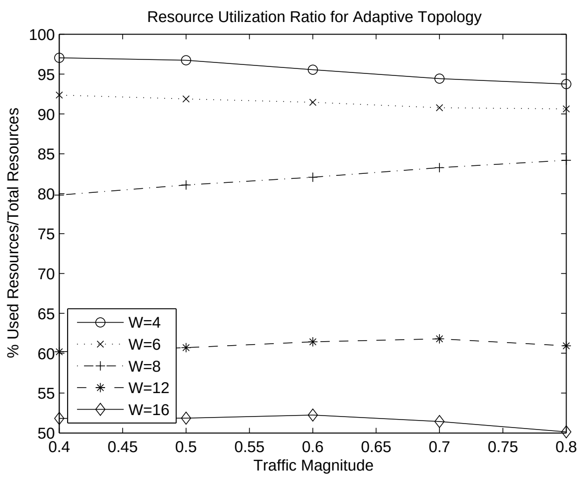


Fig. 6. Utilized wavelength resource usage ratio for adaptive topology

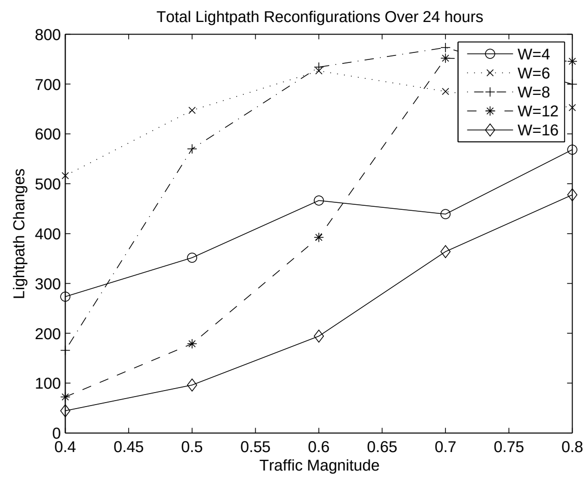


Fig. 7. Average λ-path configuration per hour for adaptive topology

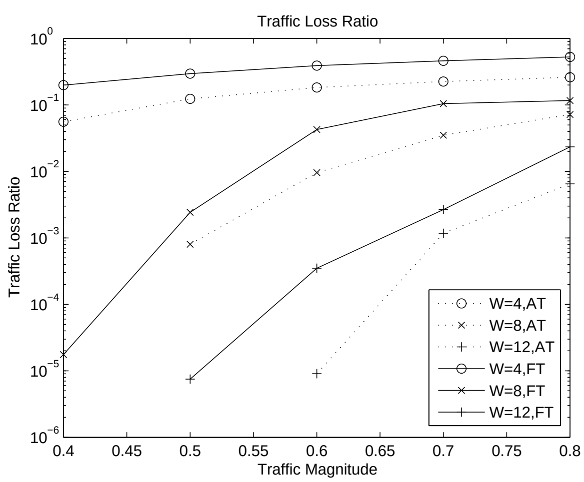


Fig. 8. Traffic loss ratios for Fixed Topology(FT) and Adaptive Topology(AT)

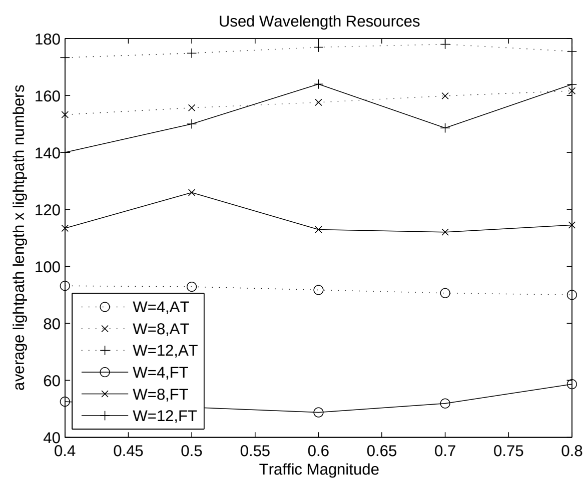


Fig. 9. Utilized wavelength resources for Fixed Topology(FT) and Adaptive Topology(AT)