Design of Protected WDM Wheel Networks under Various Traffic Conditions

Simone De Patre
Guido Maier
CoreCom
Via Colombo, 81 - 20133 Milan, Italy
Email: {depatre, maier}@corecom.it

Achille Pattavina
Dept. of Electronics and Information
Politecnico di Milano
P.za Leonardo da Vinci, 32 - 20133 Milan, Italy
Email: pattavina@elet.polimi.it

***Abstract*— Wavelength-division-multiplexing networks dimensioned for static connections could be used to accommodate an unpredictable increase of lightpath requests. We analyze the problem of the new carriers to deploy networks that provide them flexibility to deliver long-lived lightpaths on demand without capacity upgrade of the existing infrastructures. We investigate the influence of the connectivity factor in both the initial optimization and on the probability of accommodating the traffic expansion. We consider multifiber WDM “wheel” networks, a sequence of regular ring-to-mesh architectures, under various static traffic conditions. The optimization is carried out by means of a heuristic aimed at minimizing the number of fibers. The maximum allowable traffic scaling factor is evaluated by simulations with different initial network states that have already accommodated the static traffic.**

I. INTRODUCTION

When new carriers face the problem of deploying telecommunication networks that most efficiently satisfy their requirements and their prediction of traffic patterns, their interests are mainly focused on wavelength-division-multiplexing (WDM) networks that can satisfy the huge bandwidth requirements, providing cheap and reliable high-speed communications. The commercial availability of OADMs and OXCs offers a great variety of possible architectures for the optical transport layer (i.e. ring, interconnected rings or mesh) and a new dilemma could rise: mesh or ring-based topologies?

While rings are traditionally the preferred solutions in the metro area, mesh-based networks are promising for their flexibility and capability to face the traffic expansion. Many carriers deployed ring-based networks manually configuring network elements using non-standard methods, based on their own experience and on the field intuitions. Today transport efficiency has became very important, especially due to the significant changes in the type of traffic witnessed in these last years. Traditionally networks are designed with static traffic patterns or for a moderate traffic growth: when the so dimensioned networks cannot be upgraded by adding extra capacity or resizing the network elements, operators have to rely on the existing infrastructure to satisfy the new demands, or to reject them. Today network operators are unlikely to reject lightpath connections and the design of optical networks is always accomplished by forecasting a certain number of requests between nodes considering a relatively brief time period, since traffic predictions over large periods are difficult due to the dynamic nature of the emerging applications.

The traditional circuit-switched model based on the static assumption is changing rapidly as optical technologies evolve and bandwidth applications emerge: the recent attention to bandwidth end-to-end connection provisioning is also reflected in the WDM protocol standardization. A new model, known as Automatic Switched Optical Network (ASON) [1], is currently under development and its main feature is the ability to accommodate on-line connection requests.

In this paper we consider WDM network optimization and the behavior of such an optimized network when the original static traffic is expanded. We will compare architectures with increasing connectivity, starting from the simple ring topology and adding more links progressively up to the full-mesh; we call these topologies “wheel” networks. The influence of the connectivity degree is evaluated comparing the capacity requirements at the end of the optimized planning phase under static traffic and, subsequently, comparing by simulations the traffic scaling that the network can sustain when dynamic traffic is offered to the network. Section II introduces the heuristic optimization while section III describes the traffic expansion environment. Finally section IV is dedicated to the analysis of the results performed on the “wheel” networks.

II. HEURISTIC RFWA OPTIMIZATION

In a WDM network, traffic between pairs of nodes is carried through *lightpaths* which are high-bandwidth optical circuits. Two different approaches are possible to support an optical connection, depending on whether the signal is carried or not by the same wavelength along all its route. In the simplest WDM network, the lightpath maintains the same wavelength through the whole path (Wavelength Path, WP); the use of wavelength converters overcomes the *wavelength continuity* constraint and leads to the Virtual Wavelength Path (VWP) concept. The set of static requests composes the static traffic that the network must be able to satisfy by suitably configuring switching elements and by allocating transmission resources: it is elsewhere known as *virtual topology*. If traffic recovery is not supported, a connection is activated by setting up one single lightpath called *working* from the source to the destination node, otherwise the network must be able to provide *protection* resources according to proper resilient strategies.

The key aspect of designing a WDM network is solving the routing and wavelength assignment problems (RWA). The goal of routing is to select an appropriate sequence of physical links to convey the user traffic from source to destination. Routing and wavelength assignment are also coupled with fiber assignment in the case of multifiber networks (RFWA). An optimized dimensioning determines the optimum values of a set of variables, minimizing a given cost function under a set of constraints, more generally the number of wavelengths or fibers that must be provided to the WDM links so to meet the expected network performance. The routing-wavelength assignment problem in the VWP case is computationally simpler than with WP and the performance improvements in terms of static capacity requirements are not so evident in the majority of WDM networks. In our method [2] each link is a bundle of unidirectional optical fibers between two adjacent nodes and each fiber in the link hosts the same number of wavelengths W. The number of fibers per link is a design variable and the number of wavelengths W is a parameter design. Optimization is done in two steps: an initial greedy phase followed by an optimization cycle. During the greedy phase connection requests are sorted by a suitable predefined rule[1] and then the optical circuits are set up in a greedy way so that resources allocated to each one have the minimum cost. The RFWA is based on a modification of Dijkstra algorithm, running on a particular representation of the network which is the multifiber layered graph (MLG) [2]. This is a working auxiliary representation of the network state derived from the *layered graph* (elsewhere called *wavelength graph*) [4], [5].

In [2] we have extended the use of the layered graph to multifiber networks: the graph model representing the physical topology is replicated identically $F \cdot W$ times. The first W planes represent fiber 1 in all the links, planes from $W + 1$ to $2 \cdot W$ represent fiber 2, and so on; thus each plane corresponds to the given network on a particular wavelength and fiber. Horizontal arcs in the graph corresponds to WDM channels, vertical arcs connecting OXC images at the same wavelength represent space switching and vertical arcs connecting OXC images at different wavelengths represent wavelength conversion. The network state is represented by marking as "disabled" an horizontal arc of the MLG whenever the corresponding WDM channel is busy because assigned to some connection. Once suitable weights are associated to nodes and arcs of the layered graph, the Dijkstra algorithm finds the connection-path with the least total weight, thus obtaining the optimal lightpath setup according to the chosen RFWA criteria.

When a dedicated path-protected (DPP) connection has to be set up, the RFWA problem is coupled with a route-diversity search and it is jointly solved extending the Bhandari algorithm [6]. This algorithm finds the minimum cycle that can be adopted to route the working-protection (w/p) pair. This is a better solution than the simple assignment of the first minimum-weight path to the working lightpath and the second link-disjoint minimum-weight path to the protection lightpath [3]. The latter approach, called "two-step search", can in fact fail sometimes in finding feasible solutions.

The optimization cycle tries to reduce the number of partially used fibers, reallocating lightpaths routed on them on alternative routes by performing RFWA with the same criteria adopted in the greedy mapping. In this way the total number of fibers in the network is progressively reduced but there is no guarantee of success of the reallocations since the physical network with less fibers has a constrained capacity.

III. TRAFFIC EXPANSION MODEL

Traffic growth models employ the blocking probability P, defined as the ratio between the number of unsuccessful events and the total number of events occurred so far, to express the grade of service of a network. Events are lightpath requests between node pairs that arrive randomly according to a statistical process and will be eventually rejected if the rate of arrivals exceeds the rate of terminations.

Our model manages the connection request arrivals as special dynamic traffic characterized by no termination events, and it is based upon the exhaustion of the WDM network resources. This is a reasonable model since the new lightpaths are long-lived or semi-permanent and the traffic, growing in the network, eventually exhausts all the transmission capacity. Traffic expansion is modelled by a random sequence of connection requests between node pairs already connected by permanent lightpaths and, by this hypothesis, the expansion is scaled up from the original permanent traffic.

At each arrival our model applies the greedy heuristic RFWA algorithm, trying to setup the corresponding lightpath. Network resources available to support the traffic expansion are the WDM channels still unassigned at the arrival times of the requests: such channels are present in the optimized static WDM network due to the fact that optimization is never able to eliminate partially used fibers. If the needed resources are not available, the request is rejected and lost forever, since neither disruption or reconfiguration of previously permanent traffic is admissible, nor network upgrade by adding more capacity to the existing links is possible. As more and more extra lightpaths are setup during the simulation, resources for new connections continue to decrease and the blocking probability P increases. Node-pairs continue to issue new connection requests until P reaches a pre-fixed threshold value chosen at the beginning of the traffic growth simulation; after then, the simulation is stopped. For example, a threshold value $P = 0$ implies that the simulation is stopped at the first connection refusal.

Output of the simulation is the traffic increase parameter, defined as the ratio between the number of incremental connection demands accepted during the traffic-growth phase and the total number of static connections established during

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[1] Since the optimal sorting rule is unknown a priori, we have proceeded by testing different sorting heuristics. We have observed in [2], [3] that the initial choice of sorting criteria has no influence on the final optimized results.

the optimization phase (for DPP cases, static connections are doubled since each connection requires two lightpaths).

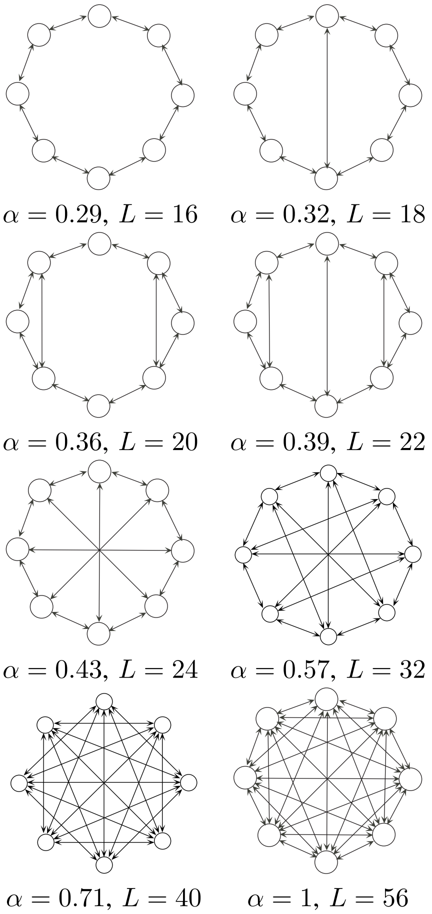
IV. RESULTS ANALYSIS

The "wheel" networks are regular or quasi-regular topologies characterized by the same number of nodes and with an increasing number of bidirectional links. If we represent the network as a graph, we use N and L to denote the number of nodes and of unidirectional links, respectively. For a network with N nodes and L links, the *connectivity factor* α, defined in [7] as $L/\left[N(N-1)\right]$, is a parameter well suited to describe the connectivity degree. Sometimes we can find also the *average node degree* [8], a topological parameter defined as $\delta = 2L/N$ measuring the average number of links terminating at a generic node. It is easily shown that $\delta = 2\alpha(N-1)$.

We select here $N = 8$ and consider a particular set of case-study topologies with $L \in \{16, 18, 20, 22, 24, 32, 40, 56\}$: thus the corresponding increase of the topological complexity can be also measured by the connectivity factor $\alpha \in \{0.29, 0.32, 0.36, 0.39, 0.43, 0.57, 0.71, 1\}$. Figure 1 shows the sequence of the case-study networks. The first topology with $L = 16$ is a ring; the next ($L = 18$) is a ring-based topology, obtained by adding one link on a ring diameter and building a pair of interconnected rings. The next two topologies ($L = 20$ and $L = 22$) are still interconnected-ring "planar" networks of 3 and 4 rings. The final four networks ($L = 24$, $L = 32$, $L = 40$ and the full-mesh with $L = 56$) are non-planar.

Before presenting the results, we will briefly describe the decisions taken about some of the design parameters that our heuristic requires, such as the initial sorting rule and the RFWA algorithm. In previous papers [2] we have analyzed the dependence of the optimized results on the design parameters and we have argued that a combination of these parameters gives results quite close to the best one obtained with ILP optimization [9]. These choices are as follows: highest priority to requests between nodes that are farthest apart and requiring the largest amount of not yet served connections; shortest path (SPR) and least-loaded (LLR) routing. All the links in the network are assumed here to have the same length, so that the cost metrics "minimum hop" and "minimum length" are equivalent in SPR-LLR. "First-fit" (FF) has been adopted for both fiber and wavelength assignment criteria (FFF and FFW). Let us also specify that the networks can be also equipped with full-capability wavelength converters (VWP network).

The goal of our study is the evaluation of the influence of network connectivity on the initial optimization and on the expansion of the connections, starting from different initial traffic conditions. In the first set of experiments, we initially assume a uniform offered traffic (one connection request between each couple of nodes, 56 requests in total). Figure 2 displays the number of installed fibers M, plotted for each value of W and function of the connectivity factor α for networks without wavelength converters (WP) and unprotected connections. As expected M decreases as the network connectivity grows. Moreover when W increases (i.e. starting from W=8 in the case of uniform and unprotected traffic), also the topology affects the optimization cycle and its results. This behavior has been proved considering also other α-equivalent networks: the presence of diameter edges diminishes the number of installed fibers, while chordal edges make them increase.


$\alpha = 0.29$, $L = 16$ $\alpha = 0.32$, $L = 18$

$\alpha = 0.36$, $L = 20$ $\alpha = 0.39$, $L = 22$

$\alpha = 0.43$, $L = 24$ $\alpha = 0.57$, $L = 32$

$\alpha = 0.71$, $L = 40$ $\alpha = 1$, $L = 56$

Fig. 1. "Wheel networks", regular topologies used to study the effect of the connectivity.

In Figure 3 we evaluate the cost implied by the provision of dedicated path protection (DPP) for a WP and a VWP network. Similar results are obtained for the two network types that highlight the substantial increase in the fiber number compared to the previous figure reporting the results for absence of path protection. The network cost increase can be expressed also by considering the ratio R between the WDM channels D_p employed for protection lightpaths and those D_w employed to carry working lightpaths: by definition R is always greater than 1. The plot of R is shown in Figure 4 for DPP uniform traffic when $W = 16$. Interestingly enough, some topologies behave better than others with a higher connectivity degree $\alpha = 1$.

Figures 5 displays the total number A of installed WDM channels as a function of the number W of wavelengths in WP (a) and VWP (b) networks for each value of the connectivity α. The parameter A is simply given by $A = MW$ and expresses the available capacity of the network after the optimization. As expected, for a given W, A decreases as the network

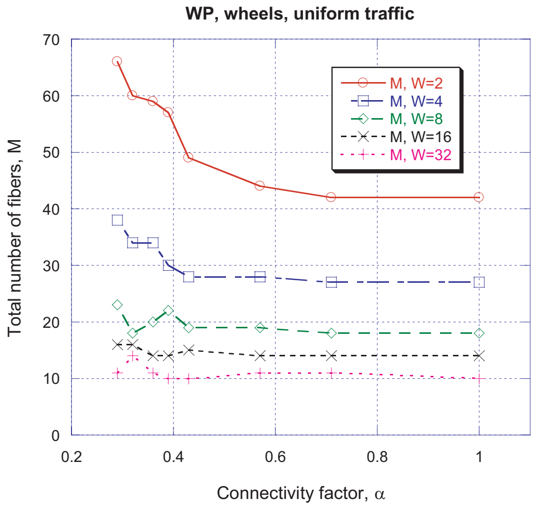
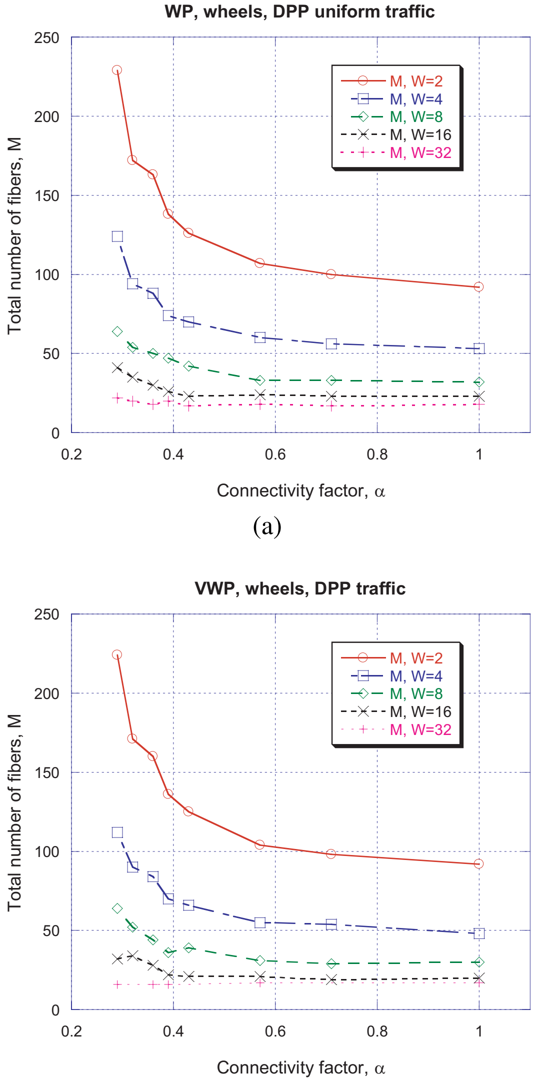


Fig. 2. Optimized number of fibers M as a function of α for unprotected uniform traffic in WP "wheel" networks.



(a)

(b)

Fig. 3. Optimized number of fibers M as a function of α for DPP uniform traffic: WP "wheel" networks (a); VWP "wheel" networks (b).

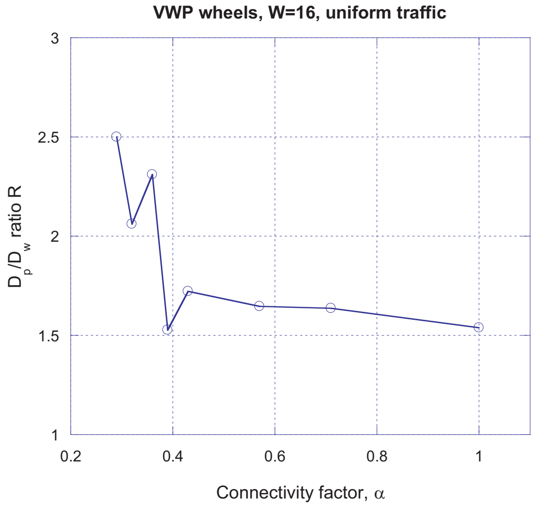


Fig. 4. D_p/D_w ratio as a function of α in VWP W=16 networks for uniform traffic.

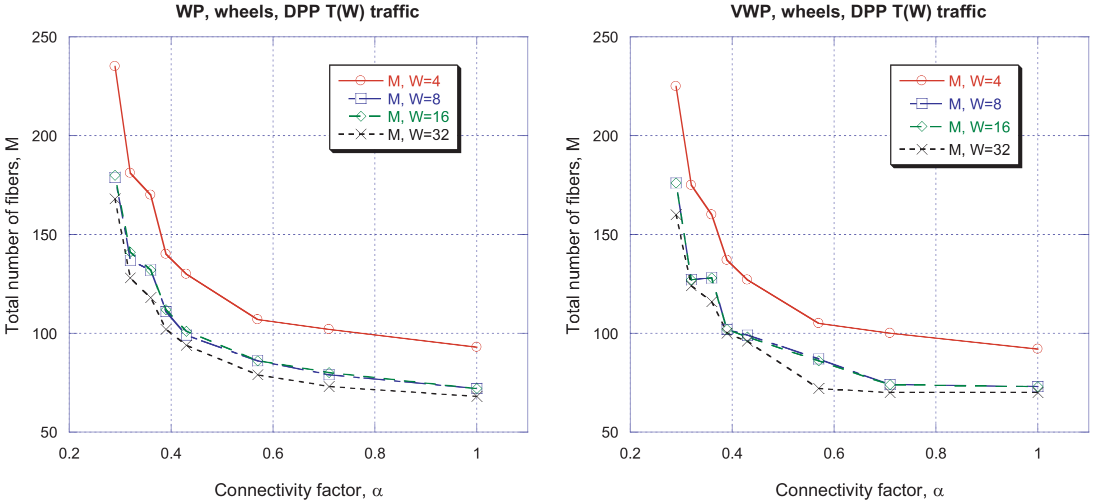
connectivity grows. However, as we can in Figure 5 (b), the advantages of a high physical connectivity tend to vanish as the number of wavelengths per fiber increases, when wavelength conversion can be exploited (VWP network). Given a traffic level, there is a value of W (32 in these experiments) by which the optimized ring becomes less "expensive" than some other wheel networks in terms of installed WDM channels.

Assuming, as we have done, that the traffic requirements consist just in one w/p pair per node couple means that, as W increases, more and more physical links are left idle by the optimization process and only a subset of the physical links of the network will be employed. If L_e is the number of links belonging to this subset, this phenomenon could be quantitatively evaluated introducing the *effective connectivity factor* α_e defined as the ratio between L_e and the number of links of the theoretical fully-connected network: i.e. $\alpha = 0.57$ and $\alpha = 1$ decrease respectively to $\alpha_e = 0.30$ and $\alpha_e = 0.32$ when $W = 32$, thus connectivity values very close to that of a ring topology. To avoid this effect, we have considered a different traffic pattern $T(W) = \lceil W \cdot L_1/[N \cdot (N-1) \cdot h_1] \rceil$ that is function of the wavelength amount. In our networks we select $h_1 = 3$ and $L_1 = 56$ that represent the average shortest cycle (in number of hops) and the number of links of the full-mesh network ($\alpha = 1$). It can be noted that, if SPR is chosen as routing criterion, $T(W)$ guarantees that all the physical links will be employed to route the static connections at the end of the optimization process, avoiding the previous behavior.

Figures 6 and 7, which refer to the case of the input traffic $T(W)$ for DPP connections in WP (a) and VWP (b) networks, confirm the previous comments about network connectivity: a small increment of α from the ring leads to almost the same performance of the full-mesh case. We can see that the number of fibers decreases significantly as α increases for wheels with a low meshing degree. On the other hand such decrease is very limited when we approach a fully meshed network. As we

(a) (b)

Fig. 5. Number of installed WDM channels A as a function of W for DPP uniform traffic: WP "wheel" networks (a); VWP "wheel" networks (b).



(a) (b)

Fig. 6. Optimized number of fibers M as a function of α for DPP T(W) traffic: WP "wheel" networks (a); VWP "wheel" networks (b).

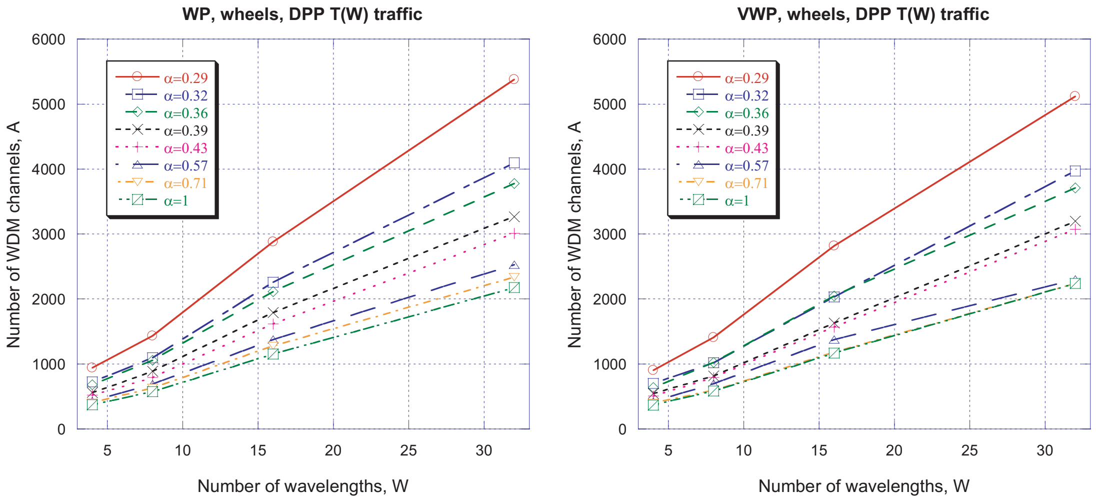
obviously expected, the number of installed WDM channels A increases with W under $T(W)$ traffic; it is observed that with certain topologies wavelength conversion leads to a slightly lower number of available channels A.

Figure 8 shows the percentage of the capacity unutilization $U = 100(A - (D_w + D_p))/A$ for the two traffic conditions when fibers in the links host W=16 wavelengths and when networks are provided with wavelength conversion capability. As we expected, if the amount of offered traffic is larger, such as the T(W) traffic, the unutilization problem is inherently less critical for most of the connectivity values.

The next graphs in Figure 9 show the incremental traffic that a VWP network with $W = 16$ can accept, measured assuming a blocking parameter $P = 0$. The traffic expansion is plotted as a function of the connectivity α and incremental connections are assumed to be all unprotected. Unlike the work presented in [10], here optimized networks have not been re-dimensioned by adding extra amount of wavelengths per fiber: the idle WDM channels available for traffic expansion are just the inefficient spots U of the optimized networks. Figure 9 clearly shows that, for W=16, the traffic expansion scales up with the unused capacity U: hence the results of the traffic incremental phase depend significantly on the efficiency of the heuristic optimization (compare Figs. 8 and 9). For T(W) conditions, most of the WDM links are heavy employed and the $(D_w + D_p)/MW$ ratio measuring the average network link load tends to be 1: as a consequence the traffic expansion is very limited. The high scaling for multi-rings α values also proves that heuristic optimization is not able to reach the absolute minimum value of M.

V. CONCLUSIONS

We have examined design and performance issues of a family of optical networks with increasing connectivity de-



(a) (b)

Fig. 7. Number of WDM channels A as a function of W with DPP T(W) traffic: WP “wheel” networks (a); VWP “wheel” networks (b).

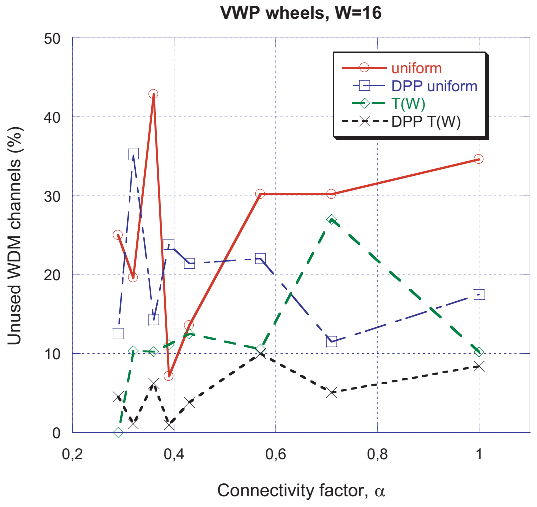


Fig. 8. Unutilization (%) of network links with W=16 in VWP networks.

grees such that the network topology spans from a ring network to a full mesh network. Networks with unprotected and dedicated-path protected connections have been compared under two different traffic conditions. The application of the heuristic approach for network design optimization under static traffic gives interesting hints about the most convenient solutions that can be adopted, based on the characteristics of the optical network (number of wavelengths per fiber, wavelength conversion capability). We have also shown how the different network topologies are capable of accommodating the incremental dynamic traffic after the design phase based on the static traffic.

REFERENCES

[1] ITU-T Recommendation, *Architecture for the Automatically Switched Optical Network ASON*, 2001, no. G.8080.

[2] G. Maier, A. Pattavina, L. Roberti, and T. Chich, “Static-lightpath design by heuristic methods in multifiber WDM networks,” in *Proceedings, Opticomm 2000 SPIE Conf.*, Oct. 2000, pp. 64–75.

[3] A. Dacomo, S. D. Patre, G. Maier, A. Pattavina, and M. Martinelli, “Design of static resilient WDM mesh-networks with multiple heuristic criteria,” in *Proceedings INFOCOM’02*, 2002.

[4] I. Chlamtac, A. Farago, and T. Zhang, “Lightpath (wavelength) routing in large WDM networks,” *IEEE Journal on Selected Areas in Communications*, vol. 14, no. 5, pp. 909–913, June 1996.

[5] C. Chen and S. Banerjee, “A new model for optimal routing and wavelength assignment in wavelength division multiplexed optical networks,” in *Proceedings, IEEE INFOCOM*, vol. 2a.4.1-8, 1996, pp. 164–171.

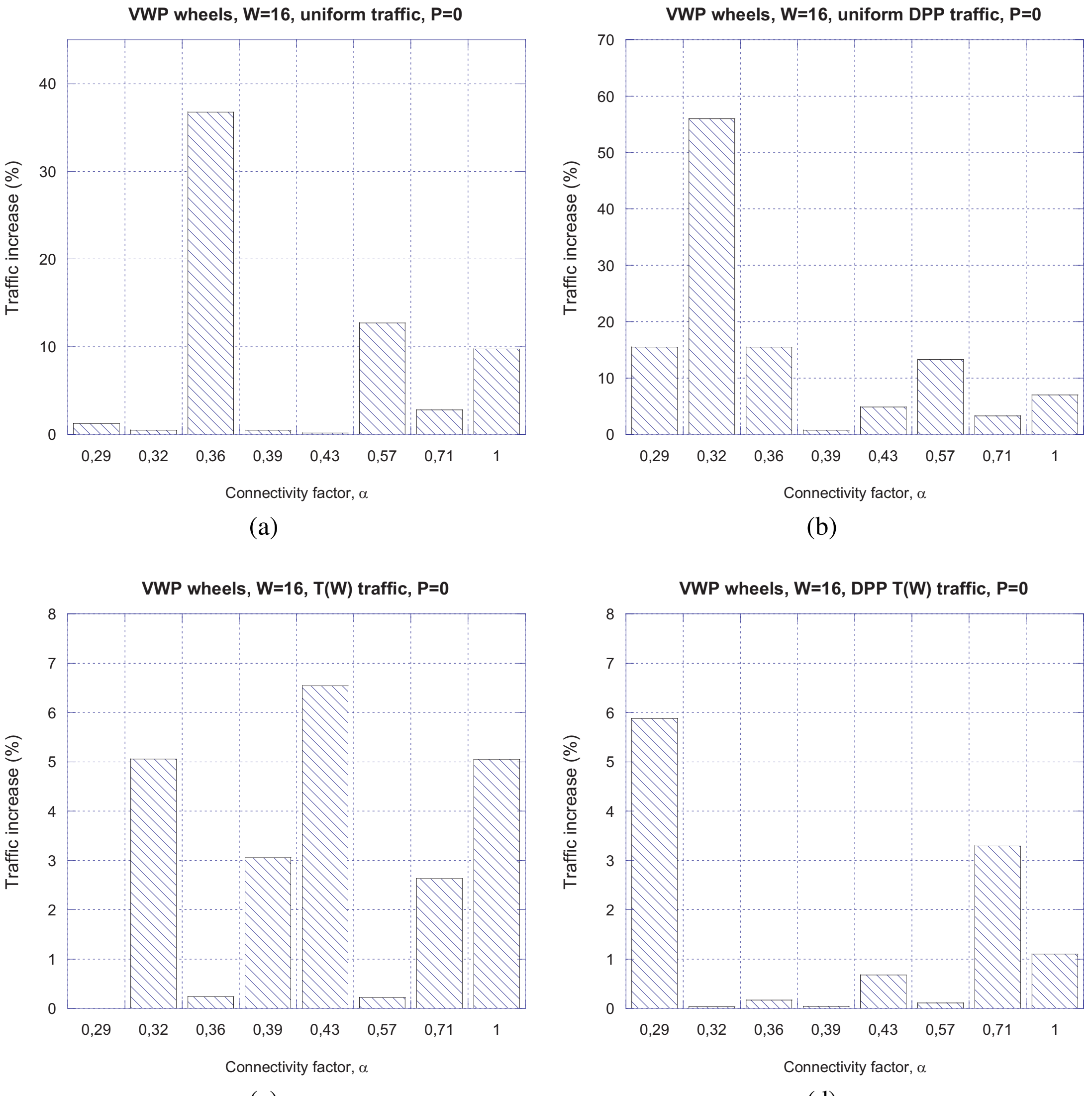
[6] R. Bhandari, *Survivable networks, algorithms for diverse routing*. Kluwer Academic Publishers, 1999.

[7] S. Baroni, R. G. P. Bayvel, and S. Korotky, “Analysis and design of resilient multifiber wavelength-routed optical transport networks,” *IEEE Journal of Lightwave Technology*, vol. 17, pp. 743–758, may 1999.

[8] J.-F. Labourdette, E. Bouillet, and A. A. Akyamaç, “Fast Approximate Dimensioning and Performance Analysis of Mesh Optical Networks,” in *Proceedings, Design of Reliable Communication Networks (DRCN), 2003*.

[9] A. Pattavina, G. Maier, and M. Tornatore, “WDM network optimization by ILP based on source formulation,” in *Proceedings, IEEE INFOCOM 2002*, vol. 3, Jun 2002, pp. 1813–1821.

[10] L. Barbato, G. Maier, and A. Pattavina, “Maximum Traffic Scaling in WDM Networks Optimized for an Initial Static Load,” in *Proceedings of ONDM 2003*, vol. 1, 2003, pp. 41–59.



(a) (b)

(c) (d)

Fig. 9. Traffic increase as a function of α in the VWP W=16 "wheel networks" under different traffic conditions and optimized with SPR-LLR-FFF-WFF: uniform traffic (a); DPP uniform traffic (b); T(W) traffic (c); DPP T(W) traffic (d).