Efficient Grooming-Oriented Heuristic Solutions for Multi-Layer Mesh Networks

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***Abstract*—An approach to design large multi-layer networks is herein proposed. Transparent lightpaths are primarily put in place to deal with demands with high values of traffic-distance product. The remaining traffic demands are then groomed and routed over both physical and virtual topologies. Deactivation of underutilized wavelengths along with configuration random perturbations are used to bring down the number of transceivers. Results are compared with exact Integer Linear Programming (ILP) models. The proposed heuristic not only approaches exact ILP results, but it also outperforms the relaxed ILP models that are focused on minimizing the link using the larger number of transceivers.**

***Index Terms*—**Heuristic, GRWA, WDM Mesh Network, Optimization.

I. INTRODUCTION

Current optical network large bandwidth capacity is provided by optical wavelength division multiplexing (WDM) technology, where one fiber can bear more than one hundred independent channels, each of which carrying several gigabits per second. However, many low-bandwidth clients/applications do not require a whole wavelength capacity and each additional wavelength in the network increases cost significantly. The number of transceivers (electro-optical transmitter and receiver) and optical cross-connects and electronic routers port count must be increased to handle larger wavelength sets. Therefore, CApital EXPenditures (CAPEX) minimization for network deployment is often focused on the reduction of the number of wavelengths [1]. Through network traffic engineering design it is possible to perform the packing of traffic demands onto as few as possible wavelengths [2]. In other words, traffic grooming should be employed as a means of lowering network CAPEX to meet a given traffic demand. Furthermore, joint optimization in multi-layer networks should encompass traffic grooming facilities at the electronic layer, routing of electronic traffic, and the assignment of a wavelength to traffic demands (GRWA). From the optical network perspective there is also the virtual topology design (VTD), which concerns how nodes are interconnected through lightpaths.

Both VTD and GRWA problems are extremely complex (NP-hard), then joint modeling for GRWA and VTD through an exact ILP model leads to feasible solutions to be found only for networks with just few nodes and sparse traffic matrices, such as [3][4]. In an attempt to find solutions to practical network scenarios, heuristic approaches (e.g. [5]) and relaxed Integer Linear Programming (ILP)

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modeling yield sub-optimal solution within reasonable running-time [6][7]. Unfortunately, most of heuristical approaches require a large number of parameters to be adapted to a specific network scenario, such as in genetic algorithms [8]. However good the outcomes, one should bear in mind that they often depend on an empirical and time-consuming search to properly weight the diverse parameters involved. As a consequence, reproducibility of results as well as their performance in other scenarios is an uncertain matter.

It is proposed and analyzed in this article a complete traffic engineering design by means of ILP, heuristic, and hybrid approaches. As mentioned before, this issue belongs to the class of NP-Hard problems. This work uses ILP models to set performance bounds to access the results of the proposed heuristic. Complete GRWA ILP models are proposed for opaque networks, while the hybrid approach apply a Traffic Grooming and Routing (GR) ILP model to a VTD solution achieved by a heuristic method in translucent networks. Note that a traffic demand can be routed through both optical and electronic layers. The VTD solution is integrated to GRWA by the reservation of a wavelength in each physical link crossed in the lightpath's route. This method is able to represent translucent optical network [10] as well as fully transparent approaches by adjusting the number of lightpaths allowed. In order to solve large network topologies, a simple heuristic approach to perform a complete traffic engineering design is proposed and analyzed. It is composed of two functional blocks, one Deterministic Improvement Function (DIF) and a Randomized Search (RS). Next Section formally introduces the problem to be solved; Section III presents the GRWA and VTD approaches. Section IV brings numerical results. Finally, conclusions are drawn in Section V.

II. Problem Description

Let an irregular mesh network with two fibers interconnecting each node pair. Assume that all physical links in the network support the same maximum number of wavelengths *Wmax*. In order to add flexibility to the grooming process, a request from source *s* to destination *d* can be divided into several lower bandwidth segments (limited by the system granularity) and routed separately. In opaque networks no wavelength continuity constraint is imposed and, as a consequence, bandwidth segments can use different wavelengths along their route. Translucent networks use a multi-layer routing scheme allowing these bandwidth segments to be routed both on electronical and optical layers i.e., through a set of opaque and transparent lightpaths. In this case, wavelength continuity constraint must be imposed on transparent lightpaths (i.e. wavelength conversion is not considered).

Fig. 1 shows a node *i* handling traffic from one of its incoming to an outgoing optical fiber, each of which bearing three wavelengths. Fig. 1 illustrates how a node i adds part of its traffic demand, drops the incoming traffic that is headed to itself, and processes transit traffic through an electronic cross-connect (EXC) making use of transceivers on wavelengths $w = 1$ and $w = 2$. Note also that there is one transparent lightpath passing through the incoming to the outgoing fiber on wavelength $w = 3$ without making use of transceiver bandwidth and demanding no EXC electronic processing.

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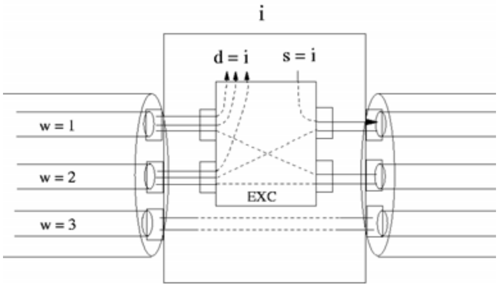

Fig. 1. Illustration for traffic processing and bypassing in a grooming node.

III. GRWA AND VTD APPROACHES

The ILP, hybrid, and heuristic methods for opaque and translucent network are presented in this Section. We gradually move from an exact ILP formulation to Min-Max relaxation of the objective function. Then, a heuristic VTD is introduced to allow multi-layer routing ILP formulations. Finally, a fully heuristic approach is presented.

A. ILP Model for GRWA and GR

The following notation is used in our mathematical models: *i* and *j*, are network nodes, bearing link *ij*; *s* and *d* are source and destination nodes, respectively; *r* is a route between *s* and *d*; and *w* is a wavelength.

Given:

$E[i][j]$: adjacency matrix. It represents the physical topology.

N: number of nodes in the network.

W_{max}: maximum number of wavelengths per link.

traf[s][d]: traffic matrix.

C: Maximum amount traffic transported on a wavelength.

Variables:

W_{ij}: number of transceivers at link *ij*.

$X_{ij,w}$: amount of traffic in link *ij* on wavelength *w*.

$XB_{ij,w}$: is a binary indicating the use of a channel in a link.

$C_{ij,w}^{sd}$: represents the amount of traffic from *s* to *d* using link *ij* on wavelength *w*.

$D_{sd,w}$: is a fraction of the traffic (traf[s][d]) on wavelength *w*.

Objective Function: Minimize the total number of transceivers used by reducing the number of wavelengths interconnecting *i* to *j*.

$$NW = \text{Min: } \sum_{ij} W_{ij} \tag{1}$$

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Constraints to GRWA:

$$XB_{ij,w} \leq X_{ij,w} \tag{2}$$

$$C \times XB_{ij,w} \geq X_{ij,w} \tag{3}$$

$$\sum_{sd} C_{ij,w}^{sd} = X_{ij,w} \tag{4}$$

$$\sum_i C_{ij,w}^{sd} - \sum_i C_{ji,w}^{sd} = \begin{cases} D_{sd,w}; & j = s \\ -D_{sd,w}; & j = d \\ 0; & \text{otherwise} \end{cases} \tag{5}$$

$$\sum_w XB_{ij,w} = W_{ij} \tag{6}$$

Description:

Expressions (2) and (3) are used to establish the relation between variables $X_{ij,w}$ and $XB_{ij,w}$. Note that the Expression (3) also restrains the quantity of traffic on a wavelength to its full capacity.

Expression (4) is a traffic grooming constraint. It shows that the sum of demands passing through link *ij* on wavelength w may not exceed $X_{ij,w}$.

Expression (5) is the flow conservation constraint. It ensures that traffic is only added in a source node and dropped at a destination node.

Expression (6) accounts for the number of wavelengths in the link *ij*.

For opaque networks one may reduce complexity by separating the wavelength assignment from grooming and routing without loss of generality. Therefore, the same assumptions made for GRWA are used to model a GR (Grooming and Routing) problem.

Variables:

X_{ij}: is the amount of traffic on link *ij*.

C_{ij}^{sd} : is the amount of traffic being used on link *ij* due to source *s* to destination *d*.

Constraints to GR:

$$\sum_{sd} C_{ij}^{sd} = X_{ij} \tag{7}$$

$$\sum_i C_{ij}^{sd} - \sum_i C_{ji}^{sd} = \begin{cases} traf[\mathrm{s}][\mathrm{d}]; & j = s \\ -traf[\mathrm{s}][\mathrm{d}]; & j = d \\ 0; & \text{otherwise} \end{cases} \tag{8}$$

$$W_{ij} \geq \frac{X_{ij}}{C} \tag{9}$$

Description:

Expressions (7) and (8) are analogous to (4) and (5), respectively.

Expression (9) states the minimum number of wavelengths needed according to the amount of traf-

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fic using link *ij* and full wavelength capacity *C*.

Min-Max Relaxation

Observe that the objective function in Expression (1) seek out the fewest number of wavelengths on a whole network basis. A relaxation is here proposed for the objective function such that the new goal in (10) is to minimize the maximum number for wavelengths on a link basis.

$$NW_{min\text{-}max} = \text{Min: Max } \{W_{ij}\} \tag{10}$$

B. Hybrid Approach to VTD, Grooming, and Multi-Layer Routing

A multi-layer routing scheme allows fractions of traffic demands to be routed both on electronic and optical layers. In order to reduce complexity, VTD is performed heuristically as follows.

1) Choosing and Routing Lightpaths: Provided that the aim is to use lightpaths to increase grooming efficiency, i.e. reduce the number of transceivers needed in comparison with opaque networks, one should expect that the placement of bypass optical connections is related to the following aspects: i) the large demand between a pair of nodes *sd*, and that ii) many hops have to be crossed from *s* to *d*. Therefore, we propose that transparent (undirected) lightpaths should be primarily provided to connect pair of nodes *sd* with higher traffic-distance product TL_{sd}, which calculated in (11).

$$TL_{sd} = Dist_{sd} \times (traf[s][d] + traf[d][s]), \tag{11}$$

$Dist_{sd}$ is the minimum number of hops between *sd* and *traf*[*s*][*d*] is the demand between *s* and *d* given by the traffic matrix. The number of undirected links in a complete graph is $N(N-1)/2$. Provided that |*E*| is de number of physical links, then *L* in (12) is the upper bound for the number of transparent lightpaths (crossing two or more hops). This is illustrated in Fig. 2 for N=5, |*E*|=7 (solid), yielding *L*=3 (dashed) lightpaths.

$$L = N(N-1)/2 - |E|, \tag{12}$$

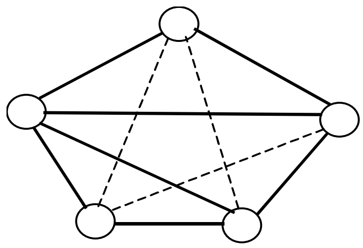

Fig. 2. Illustration for a complete graph composed of physical links (solid) and transparent lightpaths (dashed).

When *L* lightpaths are indeed used, the network diameter is reduced to just one hop turning it into a fully transparent network (i.e., no electronic processing of transit traffic). The transport of transit traffic takes part of transceivers capacity at intermediate nodes. On the other hand, for each transparent lightpath a new transceiver is needed. As a result, a limit for transceiver saving should be expected as more and more transparent lightpaths are allowed in the network.

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Lightpaths are here accommodated in the physical topology in such a way that each physical link bears between one and *Wmax* wavelengths. The shortest (available) path is then taken by each new lightpath added to the network. There are between zero and L transparent lightpaths and they are assigned according to a descending order of TL_{sd} values. Once the lightpaths are chosen and properly routed, a set with L integer linear programming (ILP) models are assembled for finding out how to optimally perform grooming and routing (GR) over traffic demands in such a network scenario encompassing transparent lightpaths as follows.

2) ILP Model for GR with Transparent Lightpaths (VTD-GR): The ILP model proposed is based on GR model. It is upgraded to take into account the constraints imposed by the transparent lightpaths that have been chosen and routed as described above. The following notation shows the differences between models.

EL[i][j]: the logical topology (transparent lightpaths) adjacency matrix.

$Wmax_{ij}$: number of wavelengths left in a physical link ij after routing and assigning transparent lightpaths ($Wmax_{ij} \leq Wmax$).

Constraints to VTD-GR: Expressions (13) and (14) should be added to (7), (8), and (9) from GR.

$$W_{ij} \leq Wmax_{ij}, \text{ if } E[I][j] = 1 \tag{13}$$

$$W_{ij} = 1, \text{ if } EL[i][j] = 1 \tag{14}$$

Description:

Expression (13) ensures that a physical link ij cannot exceed the number of wavelengths left unused by the routing of transparent lightpaths.

Expression (14) states that each transparent lightpath holds just one wavelength, i.e., the ILP model takes a transparent lightpath as a ‘new physical link’, which bears just one wavelength.

The proposed model allows wavelength continuity and assignment issues to be sorted out when choosing a route for transparent lightpaths (VTD design). The ILP model for the opaque part of the network, as described above, is naturally free from the continuity constraint. The assignment of X_{ij} (and C_{ij}^{sd}) to a particular wavelength w is based on local and independent variables (i.e., does not involve other nodes than their adjacent) and can be performed afterwards at a post-processing stage. Thus, the result is a very efficient hybrid model able to handle medium size networks.

C. Fully Heuristic Approach to VTD, Grooming, and Multi-Layer Routing

Fig. 3 shows a diagram to illustrate the proposed fully heuristic method. It takes as input data the network physical topology and the traffic demand matrix. First the lightpaths are chosen by the VTD method presented above, and then the heuristic procedure will use the transparent lightpaths, along with physical topology, to accommodate the traffic demands, which is routed using a set of k-shortest available path to create the initial scenario. Different number of iterations can be performed using DIF and RS to reduce de number of transceivers in the network configuration.

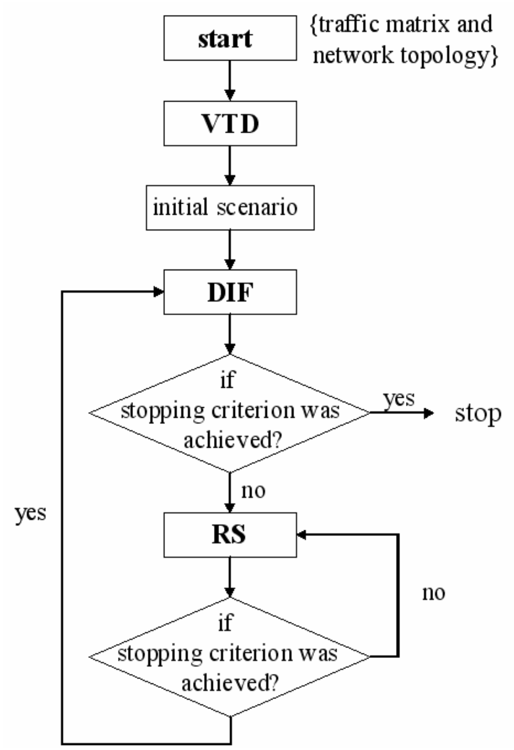

Fig. 3. Heuristical approach for Grooming in multi-layer networks

Pseudocode for the functional blocks in Fig. 3 are given bellow along with its respective description.

Algorithm 1 Initial Scenario

for each node pair s*d*
  aux = traf[*s*][*d*]
  for each *k* path of *sd*
    for $w \in \{1,...,W\}$
      if *Available_Bandwidth* (*k*,*w*) ≥ aux **then**
        allocate *aux* along path *k* on wavelength *w*, and go to next *sd*
      else allocate the *Available_Bandwidth* (*k*,*w*) along path *k* on wavelength *w*
        aux = *aux* – *Available_Bandwidth* (*k*,*w*)
    end for
  end for
end for

Initial Scenario Description:

First the set with *k*-shortest paths between each *sd* is found thorough Yen´s algorithm [11] and this set is supplied as an input to this functional block. The function *Available_Bandwidth*(*k*,*w*) finds out

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the availability along route *k* when using wavelength *w*. In case it can accommodate the whole traffic demand between *sd*, this path will be used. Otherwise, only part of this demand will be served. Therefore, a demand *sd* can be partitioned and routed along different paths aiming at transceiver maximum capacity utilization.

The initial scenario leads to a given number of transceivers per link (limited at *Wmax*) being used in this network configuration *Net*, which bears the following paraments of a multi-graph $G = (V,E)$.

- $|E|$: represents the number of edges, in the set *E*.
- $|EL|$: number of lightpaths, in the set *EL*.
- $|D|$: number of demands, in the traffic matrix *traf*[*s*][*d*].

Each lightpath $l = 1, \ldots ,|EL|$ uses one wavelength from $e \in E^*$, where $E^* \subset E$. The lightpath must comply with the wavelength continuity constraint. Finally, the number of transceivers for a given network configuration *Net*, is represented by *NW(Net)*.

Deterministic Improvement Function – DIF: This function has the goal of eliminating sub-utilized links through the simple procedure summarized in a pseudocode as follows:

Algorithm 2 DIF

Given *Net*
for $w \in \{1,...,W\}$ on ($ij \in E$ or $l \in EL$)
    if *w* in *ij* or *l* is sub-utilized **then**
        Find every demand *sd* using wavelength *w*
        Reroute *sd* using a path disjoint of *e* or *l*, creating new configuration *Net'*
        if *NW(Net') < NW(Net)* **then**
            accept *Net'* as the current configuration
        end if
    end if
end for

DIF description:

This procedure goes through the wavelengths in each connection with one-hop, whether a physical link or a transparent lightpath, looking for low utilization levels (i.e., below 20% capacity use). When it finds a *w,* either along *e* or *l,* meeting this criteria, the algorithm attempts to reroute all demand *sd*, such that each new route must be disjoint from link *e* (or lightpath *l*), in order to eliminate this transceiver from *Net*. These alternative disjoint routes are chosen from minimal hop count *k*-shortest path algorithm.

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Randomized Search – RS: It performs a random perturbation in the current solution by rerouting a given *sd* traffic demand. This function may also prevent DIF algorithm from getting trapped in a local minimum.

Algorithm 3 RS

Randomly choose a demand s*d*
Release the load of *sd*, through the path used to attend this demand
Randomly choose a new path to *sd*
if *NW(Net') < NW(Net)* **then**
    accept *Net'* as the current configuration
end if

RS Description:

In a network configuration *Net*, a given demand *sd* is randomly chosen and its respective load at every edge and lightpath through the route is released. Then, a new path for *sd* is randomly chosen leading to a new scenario *Net'*, which is accepted as the current configuration in case the total number of transceivers is reduced.

IV. NUMERICAL RESULTS

Results are presented for different mesh network physical topologies presented in Fig. 4. Wavelength full capacity is set at 48 units of traffic representing, for instance, OC-48 with OC-1 granularity. The random traffic matrix has demands between all nodes (full matrix) with 3, 9 or 36 units of traffic with 40%, 40%, and 20% chance, respectively. Note that traffic demands never take wavelength full capacity, so that there is always room for demands to be groomed. Opaque and translucent network configurations are investigated. Unfortunately it is not possible to use results from other previously proposed heuristic approaches since they often require a large number of empirical fitting parameters that are not made available by their authors (e.g. [8]). Nevertheless, our ILP solutions provide a solid benchmark to assess the effectiveness of our simple algorithms against optimal (but costly) results.

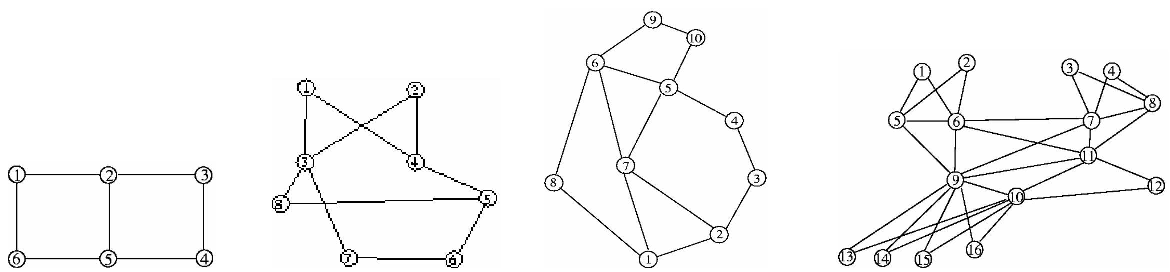

Fig. 4. Physical topologies

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A. *Opaque Networks*

In an opaque network no transparent lightpath is available, traffic demands need to be routed electronically allowing large degree of freedom for grooming-oriented network configuration solutions. The goals here are: i) to identify the effectiveness of separate and combined use of DIF and RS, and ii) to evaluate the proposed heuristic against global optimal and *min-max* solutions benchmarks.

1) Relation between DIF and RS: Table I presents the results for initial scenario, RS, DIF, and both combined, applied on network topologies with 6, 10, and 16 nodes (with 7, 14, and 30 edges, respectively). It shows the relevance of each procedure and the benefits of their combined use. The stopping criteria used is the number of iterations (10^4). It can be noted that in the 10-node network there are 3, 6, 8 transceivers saved from *k*-shortest-path initial solution when using RS, DIF, and both techniques combined, respectively. As it might be expected, these results suggest the combined use of DIF and RS. Now the proper number of iterations should be investigated using optimal solutions as bounds.

TABLE I. PERFORMANCE OF THE HEURISTIC STEPS

	6-node	**10-node**	**16-node**
initial	27	73	247
RS	24	70	234
DIF	23	67	245
RS and DIF	21	65	230

2) Convergence and Optimal Bound: The convergence of the method is shown in Figs. 5-7. The outcomes achieved for number of transceivers using GRWA and GR integer linear program (ILP) exact models set the performance benchmarks. The lower bound is given by *NW*, expression (1), which finds a network configuration (*Net)*, with the minimal total number of transceivers achieved by means of exact models. Its relaxation, $NW_{min\text{-}max}$, results in network configurations with the minimal number of transceivers at the most demanding link. The *min-max* approach, expression (10), appeals to the intuition that the whole network transceiver count is benefited as a result of focusing on the minimization of the worst-case link. In addition, $NW_{min\text{-}max}$ allows solutions (using CPLEX 9.0 [12]) for medium sized networks to be obtained within reasonable running time (an hour) while only small networks can be solved using *NW* within the same period of time. Hence, only Fig. 5 has the two optimal solutions, while Fig. 6 and 7 present only $NW_{min\text{-}max}$ reference line.

Note that the initial scenario (abscissa=0) of our heuristical approach already provides *NW(Net)* lower than $NW_{min\text{-}max}$ in Fig. 5. Moreover, considerable improvements are found via DIF and RS as the number of iteration progresses, allowing our heuristical approach to get closer to *NW*. As it is seen in Figs. 5-7, where the DIF was used once in each 10^3 RS iterations, the convergence of the method will be achieved around 10^5 iterations as no better *NW(Net)* is found beyond this point for all the investigated network scenarios.

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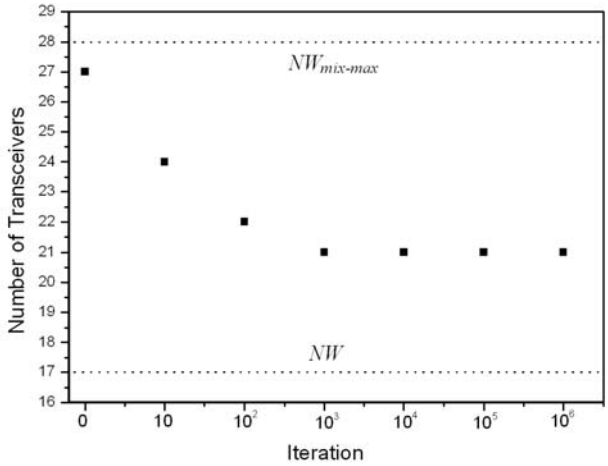

Fig. 5. Number of Transceivers vs. Iteration for 6-node network

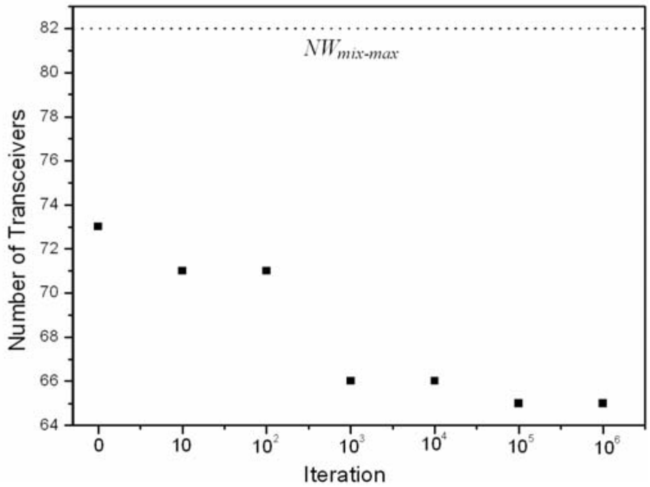

Fig. 6. Number of Transceivers vs. Iteration for 10-node network

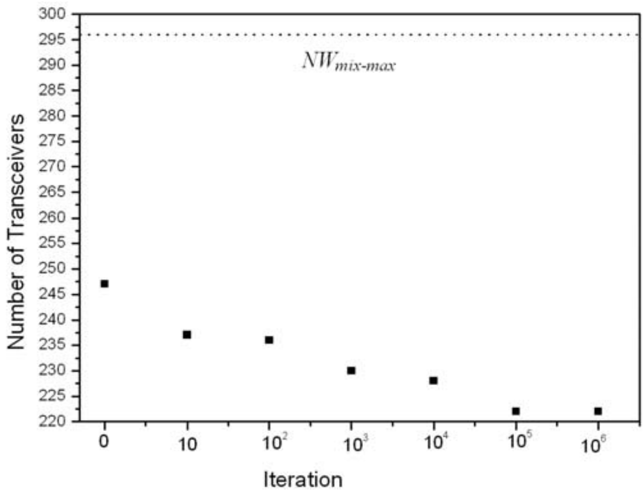

Fig. 7. Number of Transceivers vs. Iteration for 16-node network

There can be different stopping criterion besides number of iterations. For instance, minimal wavelength utilization has also been tested for DIF without success as it poses the risk of affecting more severely the whole network configuration. When a wavelength is released, all the traffic transported

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on it has to be accommodated elsewhere. This leads to severe network configuration changes that jeopardize the convergence of the method.

As far as running time is concerned, heuristics are expected to bear results much faster than ILP models. For instance, the 16-node in Fig. 7 $NW_{min\text{-}max}$ reaches 296 transceivers within one hour running time while the heuristic gets a better result (222 transceivers) in less than one minute (run on a Pentium IV 2.0GHz processor with 1GB RAM). This indicates that large networks can be dealt with this heuristic approach, either when the running time becomes prohibitive or when computation time is critical. In the latter case are network dynamic reconfiguration and traffic restoration tasks.

B. *Translucent Network*

The outcomes for translucent networks were generated under 5 random traffic matrices for topology with 6 and 8 nodes in order to provide a more general picture concerning the impact of traffic matrix on ILP solutions. VTD is implemented with $l = 0, \ldots ,L$, transparent lightpaths, meaning that outcomes were generated from opaque to fully transparent network configuration.

Figs. 8 and 9 show results for 6-node and 8-node networks, respectively, for both hybrid method and fully heuristic approach. Outcomes are presented in percentage of transceivers needed (normalized by the amount used in opaque networks) to satisfy the traffic demands against the number of transparent lightpaths allowed (but not necessarily utilized) in the network. Provided that 5 random traffic matrix instances are used, the vertical bar represents the max and min values found, while the small horizontal line crossing this vertical line represents the mean value taking all traffic matrices.

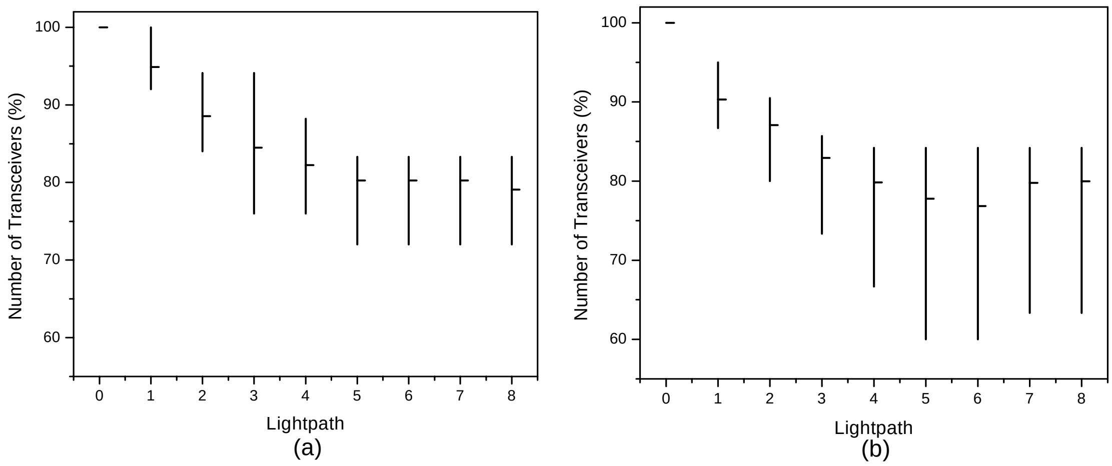

Fig. 8. Number of transceivers vs lightpaths allowed for the 6-node network to hybrid (a) and heuristic (b) approaches

It is clear that there is a consistent reduction in the number of transceivers as more transparent lightpaths are allowed for the diverse traffic matrices for both methods. However, while this reduction reaches a floor for the hybrid model, e.g., for Fig. 9(a) it is around 70%, there seems to be an inflection point for the proposed heuristic approach in Fig. 9(b).

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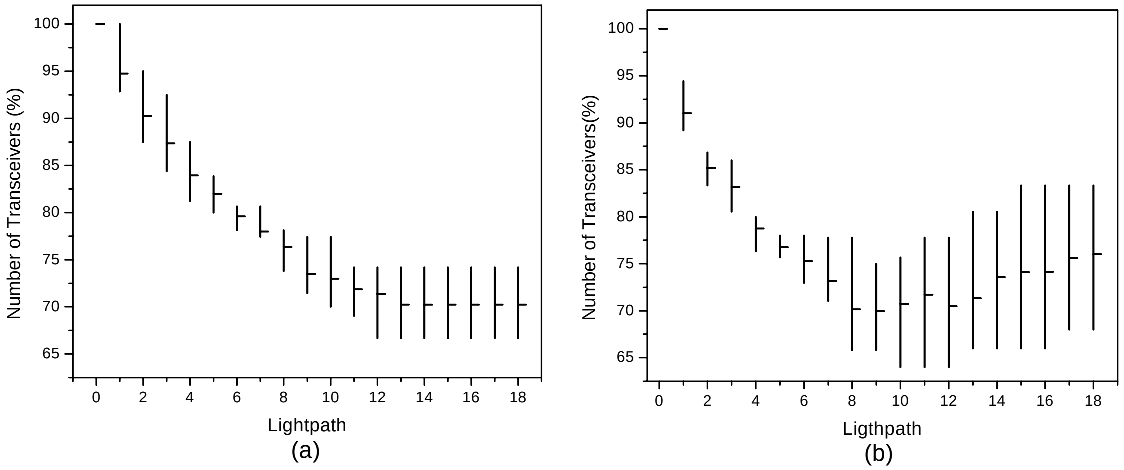

Fig. 9. Number of transceivers vs lightpaths allowed for the 8-node network to hybrid (a) and heuristic (b) approaches

Allowing more than a given optimal number of lightpaths may result in inefficiently used wavelengths in the network configuration found through our heuristic approach. Under the same circumstances, the exact model may even use the lightpaths permitted but it may leave idle physical links to meet the minimal number of transceivers goal. One should bear in mind that although the relative reductions are similar in Figs. 8 and 9 for both methods as more lightpaths are allowed, absolute minimal transceiver count reached are lower for the exact method as already seen in Fig. 5.

Another metric is here accessed for the traffic-engineering point of view: the transit traffic processing P_i stated in Equation (15). The higher is P_i, the more demands are placed on node electronic systems [13]. $P = max\{P_i\}$ indicates the highest level of node opacity in the optical network as a result of optimizing the network for minimal number of transceivers.

$$P_i = \sum_{\{s,d\}\neq i} \sum_{j} \sum_{w} C_{ij,w}^{sd} \qquad (15)$$

Fig. 10 shows electronic processing reduction (again normalized using the opaque network) found for the 8-node network under both hybrid and heuristic methods. Although the proposed heuristic leads to wider variation for different traffic matrices (see the vertical lines), it is clear that lightpaths can reduce more than 80% the need for processing transit traffic in both cases. It is noteworthy that network resilience to node failure will also benefited, since less traffic is affected when an EXC fails. Note also that even with maximum number of lightpaths L the processing of transit traffic does not reach zero. It is explained by the fact that the objective function is solely aimed at minimizing the number of transceivers; and having a one-hop network is not the most appealing option from this standpoint.

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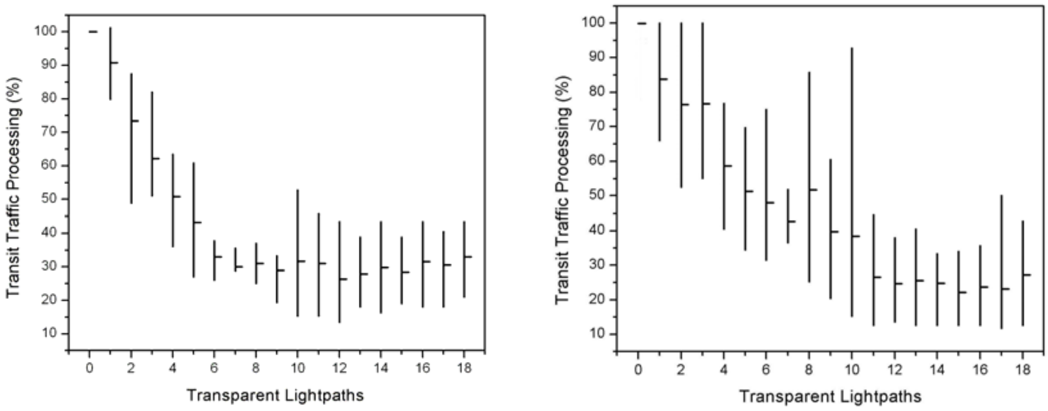

(a) (b)

Fig. 10. Processing vs Number of lightpaths for network with 8 nodes

V. Conclusion

This work proposed and assessed a simple heuristic approach to design multi-layer networks. The method first chooses (following the decreasing order of traffic-distance product) and route transparent lightpaths (through minimal hop-count paths). Then, lightpaths were added to the network and accommodated in the physical topology by putting aside a wavelength on the links used by a transparent lightpath. A deterministic improvement function and a randomized search performed the grooming, routing and wavelength assignment over the physical links and transparent lightpaths available. Numerical results were analyzed for different network scenarios. An important outcome is that the proposed heuristic outperforms relaxed ILP models in all cases investigated for opaque networks. The limited benefits of transparent lightpaths for reducing transceiver count and electronic processing were confirmed using the heuristical approach at similar level obtained by the exact ILP model. Future work will address dynamic issues such as bandwidth/lightpath provisioning, network reconfiguration, and traffic restoration.

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