A Flexible WDM Ring Network Design and Dimensioning Methodology

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Abstract: Designing arbitrary topologies based on Wavelength Division Multiplexing (WDM) rings yields a number of advantages, including fast restoration mechanisms, simple network management and control. The optimal design of such networks is however a rather complex task, with multiple objectives being optimized that can often be in conflict one with another. The paper presents a modular methodology that encompasses three fundamental steps in designing an arbitrary topology organized as a set of interconnected WDM rings. These are the selection of the Ring Cover, the Routing of the inter-ring traffic and the Traffic Balancing with Wavelength Assignment (TBWA) of the traffic locally on individual rings. After a description of the overall methodology, a detailed formulation of the TBWA problem in presence of both symmetric and asymmetric traffic demands is given. An efficient algorithm that yields sub-optimal solution of the TBWA problem is then proposed. Numerical results show that the algorithm finds an optimum solution in a number of experiments.

The original version of this chapter was revised: The copyright line was incorrect. This has been corrected. The Erratum to this chapter is available at DOI: 10.1007/978-0-387-35410-1_19

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1. INTRODUCTION

Wavelength Division Multiplexing (WDM) technology is fast becoming the de facto standard solution to the user's continuously growing demand for high bandwidth connections. At the same time, various customers nowadays demand telecommunication networks that are capable of providing highly reliable and uninterrupted service. Combined together, these two facts are creating an increasing interest in the design of survivable WDM backbones with built-in protection mechanisms available in the optical layer. In this work we focus our attention on ring-based protection mechanisms as they are often used in voice and data networks [10].

A ring based network design yields a number of advantages, including simplified management and control of the network, and fast restoration mechanisms upon link or node failure occurrence. The design of a given arbitrary topology in the form of a set of interconnected rings reduces the overall network connectivity and hence may limit the number of distinct cables that carry working fibers in the final network layout. With a reduced number of cables in the system the overall network cost may also be reduced. Due to these and other advantages, it is not surprising that ring-based network designs are often preferred to other network topologies, e.g., meshed topologies, even when these alternative solutions can statistically save up to 30-60% of the spare resources.

It is envisioned that in WDM networks too, a ring-based design shall offer advantages similar to those that are found in conventional networks. Considering that in a WDM network, the abundant bandwidth is not an expensive, nor a scarce resource, the 30-60% spare resource savings of mesh layouts may become even less critical from an overall network design viewpoint.

Multiple criteria can be defined to optimally design and dimension WDM ring-based networks. In a previous work, the authors considered the problem of minimizing the total wavelength mileage [1], defined as the sum of the working and protection wavelength miles required in the network to support a given set of traffic demands. In [1], an exact Integer Linear Programming (ILP) formulation of the problem and a simplified ILP formulation that can handle the design of large networks were proposed. In a more recent work [2] the problem of minimizing the total number of optical cross-connects ports in the network was addressed and a sub-optimal solution based on a greedy algorithm was proposed.

This paper addresses the problem of minimizing the total fiber mileage required in a given network with arbitrary topology to support a given set of traffic demands. The problem is solved assuming that wavelength converters are not available for intra-ring traffic and traffic demands are either symmetric (e.g., voice traffic) or asymmetric (e.g., client-server data traffic). The problem is defined assuming that SONET (2-fiber Bidirectional Line Switched Rings) 2f-BLSR like optical rings [10] are used to design the network. In order to design a network that is reliable in presence of either a link or a node fault, inter-ring traffic is supported through dual homing, i.e., at least two cross-connects exist that can interconnect the traffic demands between two adjacent rings.

The total fiber mileage in the network is reduced using a modular approach that consists of three fundamental steps. These are the selection of the ring cover, the routing of the inter-ring traffic and the Traffic Balancing with Wavelength Assignment (TBWA) of the traffic on individual rings. The paper briefly describes the first two steps, it then gives a detailed formulation of the TBWA problem in presence of both symmetric and asymmetric traffic demands. An efficient algorithm that yields sub-optimal solution of the TBWA problem is then presented and numerical results for a particular network configuration are shown, demonstrating that, in spite of its limited complexity ($O(F \cdot N_r^2)$ where F is the maximum number of fibers per link, and N_r is the number of nodes in the ring), the proposed algorithm reaches an optimum solution in a number of experiments.

Although only the solution of the TBWA problem is addressed in detail in this work, it must be noticed that due to its modularity, the proposed design and dimensioning methodology can be easily adjusted to optimize various objective functions. It can thus provides the designer with a fairly efficient and versatile optimization technique to design optical networks with ring-based protection schemes.

2. PLANNING METHODOLOGY

The presented approach consists of splitting the overall optimization problem into a number of sub-problems that can be handled separately and solved sequentially. On one hand, it is well known that dividing the optimization problem into sequential sub-problems may not result in an optimum solution when dealing with a specific cost function, e.g., total wavelength mileage [1]. On the other hand it offers a significant simplification of the optimization process. Consequently, more system parameters can be taken into account during the design optimization, or multiple solutions to the problem can be found in a short time interval. In addition, it yields a modular solution that enhance the versatility of the designed optimization algorithms that can thus accommodate different planning optimization criteria, and satisfy the various, possibly changing over time, designer's needs.

The planning methodology proposed in the paper consists of three steps: the ring cover of the arbitrary topology, the routing of the traffic demands between rings minimizing the number of crossconnections, and the TBWA in each ring. The variables under optimization can be modified in any of these steps to improve the final outcome of the overall design optimization.

A ring cover is defined as a set of rings such that the union of all their spans constitutes the network topology itself. Thus, a ring cover overlaid on a network topology ensures full connectivity of the network nodes. The first step is to identify the ring cover from a set of candidate rings $\boldsymbol{R}$. Having an independent set of candidate rings gives flexibility to the designer to include or exclude a certain set of rings in the design optimization. If the designer has already selected a cover for the network, that cover is then entered as $\boldsymbol{R}$ and the first optimization step is skipped altogether. In the second step every traffic demand is routed over the ring cover from the source node to the destination node. This step determines which rings a demand passes through. This step allows the designer to choose the routes (in terms of sequence of rings) either by means of some standard routing algorithm or manually. In the third step the traffic demands assigned to each ring are optimally routed (clockwise or counter clockwise) and assigned a wavelength within the ring. In this step the λ granularity of each fiber, i.e., the number of wavelengths per fiber, is taken into account as an input parameter.

Each step of the proposed planning methodology, with particular attention to the TBWA problem, is described next.

2.1 Ring Cover

First, an initial (possibly large) set of candidate rings $\{\boldsymbol{R}_1, \boldsymbol{R}_2, \ldots\}$ is generated according to the minimum and maximum number of nodes allowed in each ring. A ring cover is formally defined as a selection of rings $C = \left\{R_{n_1}, \ldots, R_{n_k}\right\}$, subset of the candidate rings, such that all nodes generating or terminating traffic belongs to at least one ring in $\boldsymbol{C}$. In addition, any ring $\boldsymbol{R}_x \in \boldsymbol{C}$ must have at least two nodes $\boldsymbol{i}, \boldsymbol{j}$ such that there is at least one other ring $\boldsymbol{R}_y \in \boldsymbol{C}$ and $\boldsymbol{i}, \boldsymbol{j} \in \boldsymbol{R}_y$. This second condition ensures that no ring in the cover is isolated, and any ring is connected to at least another ring in the cover via at least two nodes. With the above cover, traffic can be routed in such a way that any single node or link fault will not disrupt any connection. The ring interconnection can be protected with a *drop-and-continue* mechanism, or by duplication of the Network Element (NE) components. Considering the high node availability when compared to the link availability, and the fact that the *drop-and-continue* mechanism requires additional bandwidth in the rings, the solution proposed here is based on duplication of components in the ring interconnection nodes. Consequently, the scope of the paper is limited to the case of (single) link failure. Dual homing between adjacent rings may be still required to allow traffic balancing of the inter-ring traffic between the two or more cross-connects that interconnect the rings.

Many objectives can be identified while searching for an optimal ring cover, including the minimization of:

- Total fiber mileage
- Total cable mileage
- Total wavelength mileage
- Number of active spans
- Number of optical cross connects (OXC)
- Number of OXC ports
- Size of biggest OXC etc.

In this work the ring cover is selected with the objective to minimize the sum of the perimeters of the selected rings.

2.2 Inter-Ring Routing

Once the ring cover is determined the next step is to route each traffic demands across the rings, e.g., see [9]. This step confines itself to identifying the sequence of rings that a traffic demand is routed through, but not the exact physical path for the working connection. Using the shortest path algorithm it is possible to route the demands with the objective of obtaining the shortest number of rings crossed, or the smallest sum of ring perimeters, or the shortest physical path etc. In the paper the routing of the traffic demands is obtained with the objective to minimize the number of rings crossed by every demand. The routing of the traffic demands may also be done according to some additional engineering rules that are provided by the designer and that are external to this design step, e.g. availability of wavelength converters. At the end of this step every demand must be mapped into a sequence of rings, and an initial selection of the nodes cross-connecting each demand between adjacent rings has been made. Once the inter-ring routing has been determined, the traffic demands within each individual ring can be created by determining the ingress and egress points of each demand in the ring.

2.3 Routing and Wavelength Assignment in the WDM Ring

The third and last step in the design process is to find, within each WDM ring, an optimal routing and an optimal wavelength assignment. As already mentioned, among the several SONET-like optical ring architectures, the 2f-BLSR architecture is considered in the paper. In a bidirectional ring the optical channels are transmitted in both directions of the ring (clockwise and counter-clockwise), and the corresponding protection connections are routed with opposite direction. Line protection mechanism is considered. The spare bandwidth can be shared to protect several connections. Due to the fact that all the links on the ring have the same capacity, the actual capacity of the ring is determined by the capacity of the link with highest traffic load. If the optical channels are symmetric, then for every node pair *(i, j)* in the ring, the channels from *i* to *j* and the channels from *j* to *i* must use the same route. It is assumed that the number of wavelengths in the fiber is fixed and half of these wavelengths are dedicated to working connections, while the others are dedicated to protection. Wavelength conversion is allowed only at the nodes that interconnect traffic demands between rings, and only for the inter-rings traffic demands.

The objective of this step is to determine the route for the traffic demands in the ring and the working and protection wavelengths that reduce the number of fibers in the ring.

This problem can be demonstrated to be NP-hard, based on the demonstration given in [4] for a similar problem. In this section we will define the mathematical formulation of this problem. We also present a heuristic algorithm which solves this problem in $O(F \cdot N_r^2)$ time, where F is the number of fibers per link, and N_r is the number of nodes in the ring.

2.3.1 Problem Formulation for Symmetric Connections

Given a graph $G(N,E)$ representing the arbitrary topology under design optimization, we consider each ring separately. We define a graph representing each ring R as $R(N_r, E_r)$ where N_r is the set of nodes in ring R, and E_r is the set of spans in ring R.

We assume that the channel protecting a working channel must use the same wavelength assigned to the working channel. As a result, wavelength conversion between the working and the protection channels is not required when a fault occurs. Furthermore we assume that bidirectional line shared switched ring architecture is used, therefore, wavelength channels dedicated to protection can be shared among a number of traffic demands. Based on these assumptions, we formulate the following a Integer Linear Problem (ILP) formulation that minimizes the number of fibers necessary in the ring to fulfill the traffic requests and ensure 100% protection against any single link fault.

Given:

W : Maximum number of wavelength per fiber

d_{ij} : Number of bidirectional optical channels in ring R between source destination pair i,j, (sum of both intra-ring traffic and inter-ring traffic)

$P_d(i,j)$: Available path in direction d of the ring for the connection from node i to node j, where d is 1 for the clockwise direction, and 2 for the counter clockwise direction.

L_d : Set of links in the ring oriented along direction d, obviously $L_1 \bigcup L_2 = E_r$

Decision variables:

E_{ij}^{wfd} : 1 if source destination pair i,j is assigned wavelength w in fiber f in direction d of the ring
0 otherwise

L^{wfd} : 1 if wavelength w in fiber f, is assigned to some connection routed in
direction d of the ring
0 otherwise

P^{wfd} : 1 if wavelength w in fiber f in direction d of the ring is necessary
for protection
0 otherwise

F^{fd} : 1 if fiber f is in direction d of the ring is used, either for working connections
or for protection channels
0 otherwise

The problem can be formulated as follows:

$$\textit{Minimize} \quad \sum_f \sum_d F^{fd}$$

Subject to:

$$W \cdot F^{fd} \geq \sum_w (P^{wfd} + L^{wfd}), \quad d = \{1,2\} \ \forall f \qquad \textbf{(1)}$$

$$\sum_w \sum_f (E_{ij}^{wf1} + E_{ij}^{wf2}) = d_{ij} \qquad \forall i,j \in N_r \qquad \textbf{(2)}$$

$$\sum_{\{i,j \in N_r\} | l \in P_d(i,j)} E_{ij}^{wfd} \leq 1 \quad \forall l \in L_d, \forall f, \forall w, d = \{1,2\} \qquad \textbf{(3)}$$

$$\sum_{i,j\in N_r} E_{ij}^{wfd} \le K \cdot L^{wfd} \qquad d=\{1,2\}\ \forall f \quad \forall w \tag{4}$$

$$P^{wf2} = L^{wf1}\,,\ P^{wf1} = L^{wf2} \qquad \forall w,\ \ \forall f \tag{5}$$

$$L^{wfd} + P^{wfd} \le 1 \qquad \forall f \quad \forall w,\ \ d=\{1,2\} \tag{6}$$

$$\sum_{w}\sum_{f} E_{ij}^{wf1} = \sum_{w}\sum_{f} E_{ji}^{wf2}, \qquad \forall i,j \in N \tag{7}$$

$$E_{ij}^{wfl}\,, L^{wfd}\,, P^{wfd}\,, F^{fd} \in \{0,1\}$$

with $K > 0$, big enough.

The objective is to minimize the number of fibers in the ring. Restriction **(1)** permits to use at most W wavelengths for working or protection purposes in fiber f and direction d. Restriction **(2)** guarantees that the offered traffic demands are fulfilled. Restriction **(3)** ensures that on each link, in each direction, on each fiber, a wavelength can be assigned to at most 1 connection. Restriction **(4)** guarantees that if any working connection is using wavelength w in fiber f and in direction d, then this wavelength has to be assigned for working traffic and cannot be used for protection. Restriction **(5)** guarantees for each assigned working wavelength, the existence of a protection wavelength on the counter rotating fiber. Restriction **(6)** guarantees that every wavelength in each fiber is assigned to protection or working connections but not to both of them. Restriction **(7)** guarantees the use of the same route for bidirectional connection demands.

2.3.2 Heuristic Algorithm for Symmetric Connections

The algorithm comprises five steps. The routing of the demands in the ring is solved in the first four steps, the wavelengths are assigned in the last one.

Step 1. Initial Routing

Each demand is routed through the ring minimizing the number of hops.

NC_{ij}^{l} : Number of optical channels between source destination pair i-j that are crossing link l, $i,j\in N_r$, $l\in E_r$.

Step 2. Determine the Link Load

For each link, calculate the number of channels per link:

$$CL^{l} = \sum_{i,j\in N_r} NC_{ij}^{l}$$

The link l^{*} with highest traffic load is calculated as follows:

$$CL^{l^*} = \max_{l \in E_r}\left\{CL^l\right\} = \mathrm{CL}$$

Step 3. Optimize the Routing

The objective of the algorithm is to reduce CL. This maximum is reached on link l^*, $l^* \in E_r$. Then, some demands routed through l^* should be re-routed in the opposite direction of the ring.

$S = \left\{(i, j) / i, j \in N_r, NC_{ij}^{l^*} > 0\right\}$ set of demands that could be re-routed.

Repeat for each source destination pair i^*-$j^* \in S$

L'={l∈L | link l will be crossed if the connection (i*,j*) is re-routed}

$$Max2 = \max_{l \in L'}\left\{\sum_{i,j \in N_r} NC_{ij}^l\right\},$$

Number of channels i*-j* to be re-routed:

$$\Delta(i^*, j^*) = \min\left\{\tfrac{1}{2}\left(CL - Max2\right), NC_{i^*j^*}^{l^*}\right\}$$

It is easy to show that this algorithm solves the routing problem in $O(N_r^2)$ time, where N_r is the number of nodes in the ring.

Step 4. Selection of the Node Interconnection

For each external connection to the ring it is necessary to decide the interconnection node. An initial assignment was done in a previous module (Sec. 2.2), while mapping the traffic demands over the rings selected for the cover. After step 3 some working connections may have been re-routed along the ring, this has a direct impact on the OXC node selection. The OXC node selection, i.e. the ring interconnection nodes, for each demand may have to be reselected in order to guarantee that after balancing the total demand length, in terms of number of hops, is still minimal, eliminating the loops between OXC that could be produced by the balancing algorithm in each ring.

Step 5. Wavelength assignment

When the optimal routing has been obtained, these demands have to be assigned to one wavelength minimizing the number of fibers in the ring.

It is not possible to evaluate the exact number of wavelengths necessary in each ring, because wavelength conversion is not permitted, however it is possible to find a lower bound and an upper bound. The maximum number of working wavelength necessary in each direction is:

$$nww_{\max} = 2 \cdot CL - 1$$

and the minimum number is:

$$nww_{\min} = CL$$

Then ws assign each demand to a wavelength along the ring, we expect a number of working wavelengths, in each direction of propagation, to be:

$$nww_{\min} \leq nww \leq nww_{\max}$$

Then we calculate the number of fiber pairs necessaries in each link of the ring as:

$m = \left\lceil \frac{2 \cdot nww}{W} \right\rceil$, where W is the number of wavelength per fiber.

Demands are uniformly distributed among these fibers. In each fiber half of the wavelength are assigned to working connections and the other half to protection channels. This TBWA problem is solved in $O(F \cdot N_r^2)$ time, where F is the number of fibers per link

2.3.3 Problem Formulation for asymmetric connections

The formulation is the same one used for the symmetric connections, except that restriction (7) is not necessary due to the connection asymmetry.

2.3.4 Heuristic Algorithm for asymmetric connections

Step 1. Initial Routing

The same as the ones defined for symmetric traffic

Step 2. Determine the Link Loading

Same as that defined for symmetric traffic, but calculated for each direction of the ring:

$$CL^{l_1} = \sum_{i,j \in N_r | l \in P_1(i,j)} NC_{ij}^{l} \qquad \forall\, l \in L_1$$

$$CL^{l_2} = \sum_{i,j \in N_r | l \in P_2(i,j)} NC_{ij}^{l} \qquad \forall\, l \in L_2$$

The links l_1^*,and l_2^* with highest traffic load will be calculated as follows:

$$CL^{l_1^*} = \max_{l \in E_r} \left\{ CL^{l_1} \right\} \quad CL^{l_2^*} = \max_{l \in E_r} \left\{ CL^{l_2} \right\}$$

Step 3. Optimize the Routing

The objective of the algorithm is to minimize $CL = \max\left\{CL^{l^*1}, CL^{l^*2}\right\}$.

This maximum is reached in the link l*, $l^* \in E_r$. Then, some demands routed through l_1^*, l_2^* should be re-routed in the other direction of the ring. The following steps are repeated until no more connection can be re-routed, and then go to step 4.

- If $CL = CL^{l^*1}$, then $S^{l_1^*} = \left\{(i, j) / i, j \in N_r, NC_{ij}^{l_1^*} > 0\right\}$ set of demands that could be re-routed. Sort this set in decreasing order of the number of links crossed for each demand. Repeat for each pair $(i^*, j^*) \in S^{l_1^*}$

  L'={l∈L / link l will be crossed if the connection (i*,j*) is re-routed}

  $$Max2 = \max_{l \in L'}\left\{\sum_{i,j \in N_r} NC_{ij}^{l}\right\},$$

  Number of channels i*-j* to be re-routed:

  $$\Delta(i^*, j^*) = \min\left\{\left\lfloor \frac{CL - Max2}{2} \right\rfloor, NC_{i^*j^*}^{l^*}\right\}$$

- If $CL = CL^{l^*2}$, the process is similar to the previous one when $CL = CL^{l^*1}$, but with the other direction of the ring

Step 4. Selection of the Node Interconnection

The same as the one defined for symmetric traffic

Step 5. Wavelength assignment

The same as the one defined for symmetric traffic

3. NUMERICAL RESULTS

A long distance network has been selected in order to apply the above methodology.

The initial set of rings comprises 170 rings and the result obtained by ring cover optimization, as depicted in the figure 1, is formed by only 10 rings.

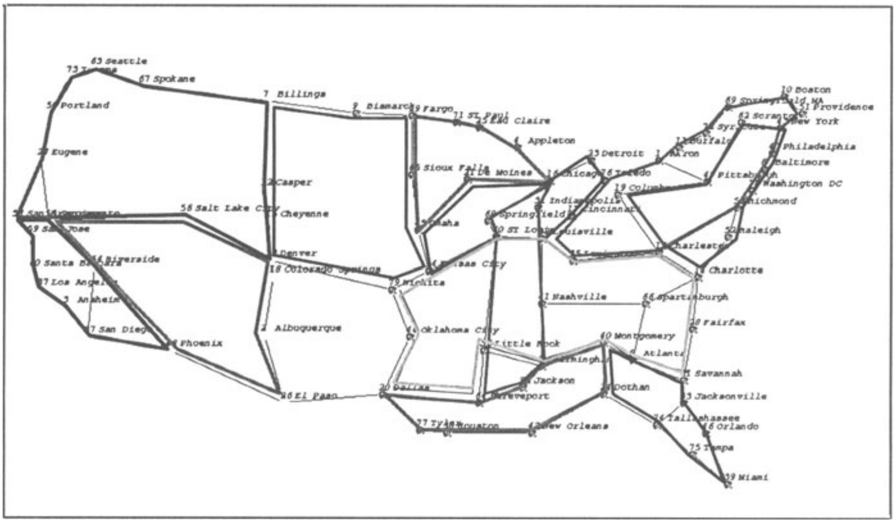


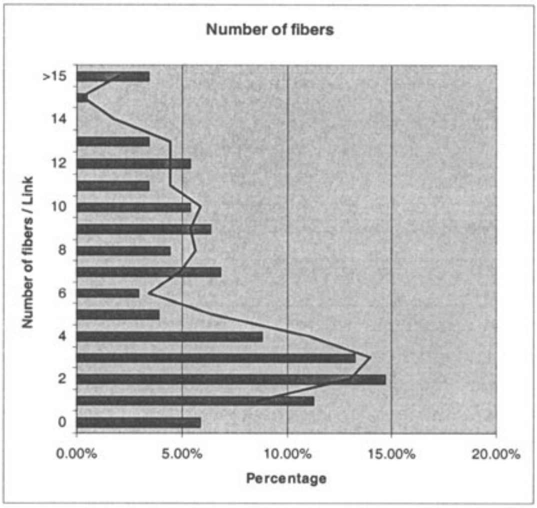
Figure 1. Ring cover result

We have applied the presented design methodology to the network in Figure 1, assuming asymmetric traffic demands. In order to illustrate the behavior of the TBA, the network has been also dimensioned without balancing the traffic in the rings. The main results are represented in the Table 1. As we can see after the Traffic Balancing the fiber length has been reduced around 20%, and around 7% the total wavelength mileage.

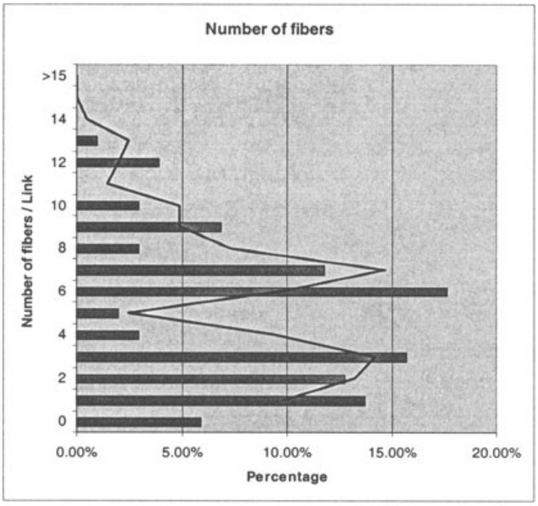
In Figure 2, for each link in the network the necessary number of fibers calculated by the proposed heuristic is reported, with and without traffic balancing. After the traffic balancing more than 15% of the links need 6 fibers. Less than 5% of the links need 4 fibers. As indicated in the figure, around 6% of the links do not need any fiber, i.e., the links are not covered. This is an acceptable result since the objective of the design is to protect all the generated demands, and not necessarily all the links of the arbitrary topology.

	No Traffic Balancing Algorithm	**After Traffic Balancing Algorithm**
Fiber Length	200,276	247,613
Working Wavelength miles	616,487	535,963
Protection Wavelength miles	1,310,450	1,541,330
Total Wavelength miles	1,926,937	2,077,293

Table 1. General Ring Dimensioning Results



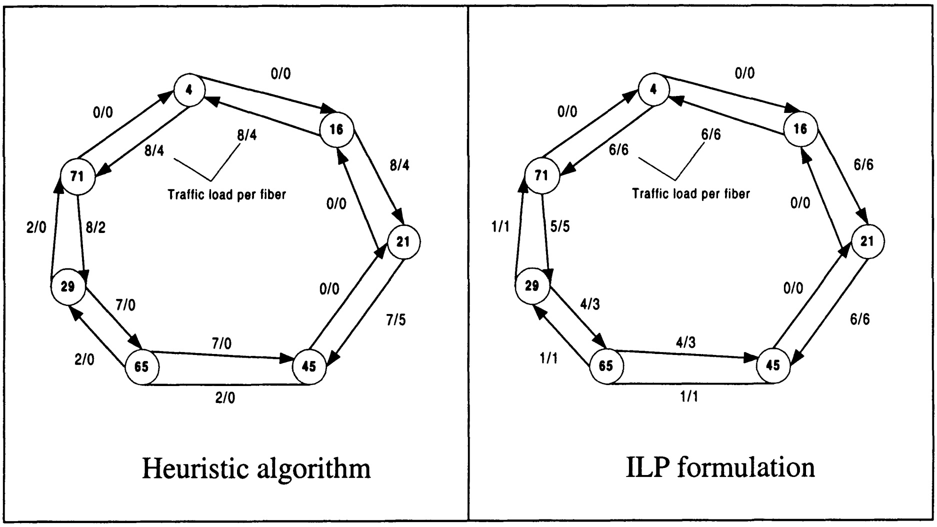
No traffic balancing algorithm



After traffic balancing

Figure 2. Ring dimensioning results

We have compared the results obtained by this algorithm with the LP formulation presented in the previous section. Although the two approaches find different solution to the TBWA problem, for every ring chosen to cover the network in Figure 1 the same number of fibers was found by both techniques. For these rings and given traffic demands, the proposed algorithm finds an optimum solution to the TBWA problem. To illustrate the difference between the results obtained by the LP formulation and the proposed algorithm, Figure 3, Tables 2 and 3 contain the routing and the wavelength assignment for one of the rings in the network. The objective of the ILP is not balancing the traffic in the ring, so in most of the cases routing and wavelength assignment obtained by each method will be different.



Heuristic algorithm

ILP formulation

Figure 3. Ring 4: Links Loading

Traffic Demands	Fiber 1		Fiber 2	
	Clockwise direction	Counter-Clockwise direction	Clockwise direction	Counter-Clockwise direction
16->21: 1	w_1			
16->45:18	w_2, w_3, w_4, w_5, w_6, w_7, w_8	w_{10}, w_{11}, w_{12}, w_{13}, w_{14}, w_{15}, w_{16}	W_1, w_2, w_3, w_4	
16->29:3		w_9		w_9, w_{10},
16->71:2				w_{11}, w_{12}
21->45:1			w_5	
45->71:2	w_1, w_2,			
Protection in the ring	w_9, w_{10}, w_{11}, w_{12}, w_{13}, w_{14}, w_{15}, w_{16}	w_1, w_2, w_3, w_4, w_5, w_6, w_7, w_8	w_9, w_{10}, w_{11}, w_{12},	w_1, w_2, w_3, w_4, w_5

Table 2. Ring 4: Wavelength Assignment obtained by the heuristic algorithm

Traffic Demands	Fiber 1		Fiber 2	
	Clockwise direction	Counter-Clockwise direction	Clockwise direction	Counter-Clockwise direction
16->21: 1			w_1	
16->45:18	$w_1, w_3, w_4, w_5, w_7, w_8$	$w_{11}, w_{12}, w_{14}, w_{16}$	w_3, w_4, w_5, w_7, w_8	w_{12}, w_{14}, w_{16}
16->29:3		w_9		w_9, w_{15}
16->71:2		w_{15}		w_{10}
21->45:1			w_1	
45->71:2	w_4		w_1	
Protection in the ring	$w_9, w_{11}, w_{12}, w_{14}, w_{15}, w_{16}$	$w_1, w_3, w_4, w_5, w_7, w_8$	$w_9, w_{10}, w_{12}, w_{14}, w_{15}, w_{16}$	$w_1, w_3, w_4, w_5, w_7, w_8$

Table 3. Ring 4: Wavelength Assignment obtained by the ILP

4. CONCLUSIONS

Due to complexity and nature of the problem, the overall optimal design of an arbitrary topology based on WDM rings cannot be obtained for practical network sizes, in sub-second time. The paper has therefore proposed a basic framework for a fast, versatile and interactive ring network design tool that circumvents the complexity problem by subdividing the optimization problem into three sub-problems. Each sub-problem is optimally resolved individually and sequentially by means of relatively simple and fast algorithms. In particular, the paper has proposed a complete methodology for designing and dimensioning optical ring based networks. A practical example was shown based on the following assumptions. 1) The ring cover is selected with the objective to minimize the sum of the perimeters of the selected rings. 2) The routing of the traffic demands is obtained by minimizing the number of rings crossed by every demand. 3) The routing and wavelength assignment for the traffic demands within each ring is determined with the objective to minimize the number of fibers in the ring. Additional optimization modules may be added as and when the design objective changes. Moreover, with the proposed design methodology the intermediate results at the end of every optimization step can be observed and manipulated by the designer. In conclusion, the paper has presented a practical and versatile approach to designing WDM ring based networks.

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