Near-Optimal Design of WDM Dual-Ring with Dual-Crossconnect Architecture *

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ABSTRACT

Survivability to faulty components and simplified management drive the practical deployment of ring-based WDM networks. In many applications, location constraints and user scalability require that multiple rings are interconnected to form a single large network. Survivability of connections spanning across multiple rings is then achieved by resorting to dual-interconnection, i.e., two (or more) nodes are available to crossconnect the inter-ring traffic between two neighboring rings. By providing one backup crossconnect-node to be used in case of failure of the primary crossconnect-node, network wide connectivity is thus guaranteed also in presence of any faulty node.

This paper addresses the problem of optimally provisioning both bandwidth and crossconnect ports required to satisfy a set of traffic demands in a dual-interconnected WDM dual-ring network architecture. The problem is solved under two design scenarios. In the first scenario, priority is given to the minimization of the number of wavelengths. In the second scenario, priority is given to the balancing of traffic between the crossconnect-nodes. Two efficient approaches are proposed that provide a near-optimal solution in each considered scenario. The discussed performance comparison provides the network designer with a quantitative assessment of the trade-off between the two approaches.

1. INTRODUCTION

Wavelength Division Multiplexing (WDM) technology offers a viable solution to fully exploit the enormous bandwidth available in fiber optics. However, this practical advantage may be compromised by the possible occurrence of a network element fault. For instance, a link failure in a 40 wavelength system, each carrying OC48 SONET signals, can affect as many as 1,200,000 telephone calls.

Protection planning has therefore become a mandatory step in the design phase of WDM networks. A number of network architectures have been proposed to take full advantage of

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WDM technology in that respect.[1–3] Among the most often chosen solutions, WDM rings present some peculiar features.

- Due to the topological layout of a bidirectional ring, only two disjoint routes exist between each node pair. When the WDM ring is in a functional state, routing is a binary decision, i.e., clockwise or counterclockwise route. Whenever a network element fault occurs, one of the two routes becomes unavailable, making it simple to promptly determine the necessary steps to circumvent the faulty element.
- The low nodal degree of the ring architecture enables simplified management and control.
- The previous two properties result in the possibility to implement Automatic Protection Switching (APS) techniques directly in the WDM layer, with the potential to achieve fault recovery times in the order of tens of milliseconds.

Although ring-based WDM network infrastructures are robust to malfunctioning nodes or links and are inherently fault-tolerant and self-healing, the limited reach of a single WDM ring network does not suit applications in which large networks are required. To overcome this limitation, interconnected WDM ring networks are considered.[4,5] Rings can be interconnected to form an arbitrary topology. The high connectivity of an arbitrary mesh is combined with the easy management and self-healing properties of the ring topology. Neighboring nodes are interconnected using either the single-homing or dual-homing architecture. In the *single-homing* architecture,[2] a single crossconnect-node[†] is used to interconnect the inter-ring traffic between two neighboring rings. This solution is sensitive to node faults, as a failure of the crossconnect-node completely disrupts all inter-ring traffic. To cope with the above type of fault, the *dual-homing* (or *dual-interconnected*) architecture is used.[6] With this architecture, rings are interconnected using two crossconnect-nodes. When one fails, the other is used to carry the entire inter-ring traffic.

Various algorithms have been proposed to optimize the performance and cost of multi-ring networks. Shi and Fonseka[6] propose a hierarchical ring architecture to interconnect nodes at different locations. The objective considered is to find the best set of rings in order to minimize the inter-ring traffic and the total cumulative ring perimeter. The ring selection is dependent on the traffic pattern. Wang and Mukherjee[7] introduce the concept of hyper-ring. The hyper-ring is a logical ring superposed on the dual-interconnection of two rings. The resulting network allows to handle inter-ring traffic in the form of intra-ring traffic using the hyper-ring.

The objective of this paper is to minimize the cost of the dual-interconnected WDM dual-ring architecture. Two cost factors are considered:

- the ring load parameters, l_{max1} and l_{max2}, which indicate the number of wavelengths required in each ring, respectively — the wavelength costs is directly proportional to these parameters;

[†]In the remaining of the paper, nodes that are used to interconnect traffic from one ring to another are referred to as crossconnect-nodes.

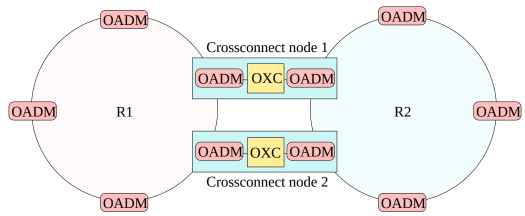


Figure 1. Ring interconnection architecture

- the crossconnect-node unbalance factor, δ_{xc}, that is proportional to the load difference at the two crossconnect-nodes — the complexity of the protection switching procedure in case of a crossconnect-node fault is proportional to this factor.

Optimization of one cost factor does not necessarily lead to the optimization of the other. On the contrary, it may happen that the minimization of the crossconnect-node unbalance factor, δ_{xc}, will lead to a higher value of l_{max}, and vice versa.

Two efficient algorithms are proposed in the paper that provide the network designer with alternative near-optimal network layouts, with respect to the two chosen cost factors. Both algorithms minimize the two cost factors, giving priority to the first or the second cost factor, respectively. Both algorithms run in polynomial time. The performance comparison discussed in Section 4 provides a quantitative evaluation of the trade-off between the two proposed approaches. Based on these results, network designers can choose the approach that better suits their cost objectives, while at the same time guaranteeing 100% survivability of the resulting network against any single network element fault, i.e., node or link fault.

2. DUAL-RING NETWORK WITH DUAL-INTERCONNECTION

The WDM network under consideration comprises two bidirectional WDM rings (dual-ring), $R1$ and $R2$, respectively, that are bi-connected by means of two crossconnect-nodes (dual-interconnection). All nodes are equipped with optical add-drop multiplexers (OADM). Each crossconnect-node comprises two OADM, one for each ring. The two OADM are interconnected by means of an optical crossconnect (OXC) as shown in Figure 1. This architecture allows to have two independently managed logical rings, even if the two rings share the physical link that connects the two crossconnect-nodes. All nodes are equipped with full wavelength conversion capability. Optical channels, or lightpaths, can thus be set up between any node pair, without being restricted to satisfy the wavelength continuity constraint — when wavelength conversion capability is not available, a lightpath must be assigned the same wavelength on each link along its route.

Survivability to any single network element failure is achieved by means of the line protection mechanism (BLSR).[2] With this protection mechanism, only the two nodes adjacent to the faulty element need to detect, locate, and take action to survive the fault. Other nodes need not take any action. With the BLSR mechanism the number of protection wavelengths in the clockwise (counterclockwise) direction required in the ring equals the number of wavelengths required by the lightpaths routed along the counterclockwise (clockwise) direction on the most loaded link of the ring. In presence of symmetric routing of the lightpaths[‡], parameter l_{max1} (l_{max2}) indicates the number of wavelengths required by the working lightpaths on the most loaded link of ring $R1$ ($R2$). The total number of required wavelengths on $R1$ ($R2$), including working and protection, is thus $2l_{max1}$ ($2l_{max2}$) in each direction of propagation. Note that within each ring, OADM have the same size. The number of wavelengths in each ring may however differ.

The provided protection wavelengths suffice to ensure protection against single node faults too. However, as explained next, the signalling and switching functions required in the event of a crossconnect-node failure are more complex when compared to a link or a (regular) node failure case. In presence of a crossconnect-node failure, in addition to the BLSR mechanism performed in each ring, the backup crossconnect-node must distinguish between those lightpaths that are routed across both rings (the inter-ring lightpaths) and those lightpaths that are routed within a single ring (the intra-ring lightpaths). Different recovery mechanisms are required at the backup crossconnect-node to deal with the two sets of lightpaths (Figure 2). With respect to intra-ring lightpaths, the backup crossconnect-node behaves like any other ring node. With respect to the inter-ring lightpaths the backup node must crossconnect them from one ring to the other. The complexity of the recovery mechanism required for the inter-ring lightpaths is proportional to the number of such lightpaths that must be recovered. For a given total number of inter-ring lightpaths, even splitting of the inter-ring lightpaths between the two crossconnect-nodes minimizes the complexity of recovery mechanism in the worse case scenario, i.e., when the fault hits the more loaded crossconnect-node. In general, however, traffic may not be balanced between the two crossconnect-nodes. This fact exacerbates the complexity of the recovery mechanism at the crossconnect-node. A parameter that characterizes such extra complexity is thus the crossconnect-node unbalance factor δ_{xc}, defined as the difference between the number of inter-ring working lightpaths assigned to each crossconnect-node, normalized to the total number of inter-ring lightpaths. In case of a crossconnect-node failure, the crossconnect-node unbalance factor, δ_{xc}, has a direct impact on the complexity of the recovery mechanism at the crossconnect-node, and thus on the network recovery time. When $\delta_{xc} \to 0$ the recovery time for a fault occurring at the more loaded crossconnect-node is minimized. When $\delta_{xc} \to 1$ the recovery time for a fault occurring at the more loaded crossconnect-node is maximized.

Determining the routing solution that yields the minimum required total number of wavelengths while at the same time balancing the inter-ring traffic between the crossconnect-nodes is not a straightforward problem.

3. PROBLEM DEFINITION

The WDM network is modeled as a graph $G(N, L)$. Set L represents the links. The set of vertices, N, represents the nodes of the network. Except for crossconnect-nodes, each (regular)

[‡]For each lightpath routed from node i to node j, a symmetric lightpath is routed using the same route, just with opposite direction of propagation, from node j to node i.

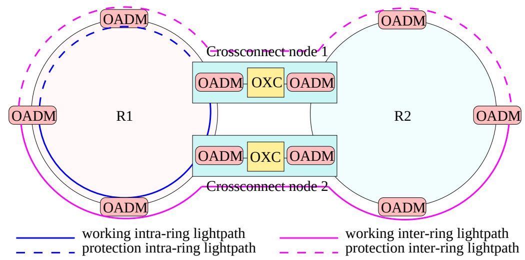


Figure 2. Protection lightpaths in case of crossconnect-node 2 failure

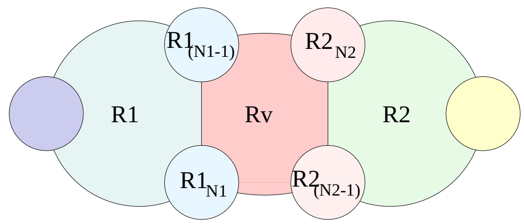


Figure 3. Network model and artificial third ring

node is represented by a distinct vertex. Each crossconnect-node is represented by two vertices: each vertex represents the interface of the crossconnect-node towards one ring. The proposed modeling graph contains a third *artificial* loop or ring, Rv, as illustrated in Figure 3. The graph can thus be logically subdivided into three rings: ring $R1(N1, L1)$, ring $R2(N2, L2)$, and ring $Rv(Nv, Lv)$.

It is assumed that the traffic demands are symmetric: for every node pair (i, j) in the network the amount of traffic going from node i to node j is the same as the amount of traffic going from node j to node i. Furthermore, it is assumed that a demand from node i to node j is routed on the same route, just with opposite direction of propagation, of the corresponding demand from node j to node i. The traffic demands are divided into two sets. Intra-ring traffic demands: the endpoints of such demands belong to the same ring, i.e., $R1$ or $R2$. It is assumed that such demands are accommodated using lightpaths that are entirely routed through a single ring only. Inter-ring traffic demands: one endpoint of these traffic demands belong to $R1$, while the other belongs to $R2$. These traffic demands are accommodated using working lightpaths that are routed across one of the crossconnect-nodes.

Traffic demands are represented by three matrices:

- matrix I^1: the intra-ring traffic in ring $R1$. Each entry represents the number of lightpaths requested from node i to node j, $\forall\ i, j \in N1$
- matrix I^2: the intra-ring traffic in ring $R2$. Each entry represents the number of lightpaths requested from node i to node j, $\forall\ i, j \in N2$

- matrix X: the inter-ring traffic. Each entry represents the number of lightpaths requested form node i to node j. Nodes i and j do not belong to the same ring.

The problem consists of fulfilling each lightpath request, while providing enough spare capacity to enable the WDM network to overcome any single[§] network element failure. The problem is solved under two alternative optimization scenarios. In both scenarios the load on the most congested link (l_{max1} and l_{max2}) and the crossconnect-node unbalance factor δ_{xc} are minimized. In the first scenario priority is given to the minimization of the load on the most congested link. In the second scenario priority is given to the minimization of the crossconnect-node unbalance factor.

3.1. Link Balancing First (LBF) Algorithm

A heuristic algorithm is proposed to solve the optimal design problem by first minimizing the load of the most congested link, l_{max1} and l_{max2}, then optimizing the crossconnect-node unbalance factor, δ_{xc}.

The algorithm consists of two steps.

1. In the first step, every inter-ring traffic demand is temporarily cut to form two intra-ring traffic demand segments, one in each ring. The two intra-ring traffic demand segments generated from the same inter-ring traffic demand are then routed independently in each ring, without paying attention to *space continuity* at the crossconnect-nodes. In each ring (say $R1$), the load of the most congested link is reduced by *independently* balancing the traffic in the ring. A modification of the INDES algorithm[8] is used here to balance the ring traffic starting from an initial routing, i.e., shortest path routing for all traffic demands. Traffic demands are then rerouted (using the opposite direction) whenever rerouting yields decreased load of the most loaded link, l_{max1}. The INDES algorithm is modified to handle the traffic demand segments generated from the cut of the inter-ring traffic demands in a special way. Notice that each traffic demand segment may choose either crossconnect-node as one of its end-nodes within $R1$, and such choice may influence the values of l_{max1}. When rerouting a traffic demand segment generated from the cut of an inter-ring traffic demand, only two solutions are allowed (see Figure 4):

    - the traffic demand segment is routed clockwise in ring $R1$ ($R2$) and its crossconnect-node is $R1_{(N1-1)}$ ($R2_{(N2-1)}$)
    - the traffic demand segment is routed counterclockwise in ring $R1$ ($R2$) and its crossconnect-node is $R1_{N1}$ ($R2_{N2}$).

    The advantage of this approach is to have a set of traffic demands that are handled in the same way as they would be handled in the single stand alone ring (intra-ring lightpaths), with the only difference that some demands have one *variable* end-point (segments generated from inter-ring traffic demands). Notice that when balancing is

[§]Both link and node failures are considered.

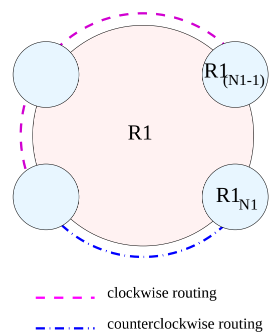


Figure 4. Inter-ring traffic rerouting strategy on ring $R1$

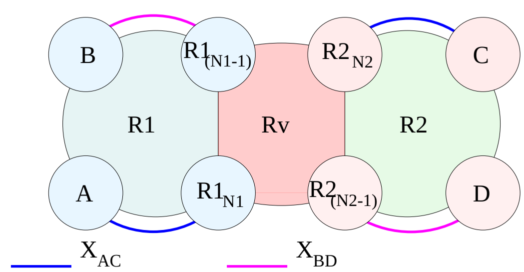


Figure 5. LBF algorithm first step possible outcome

complete, the result found for l_{max1} (l_{max2}) is a lower bound as the resulting load for link $(R1_{(N1-1)}, R1_{N1})$ ($(R2_{(N2-1)}, R2_{N2})$) may be underestimated due to the lack of space continuity of the inter-ring traffic demands at the crossconnect-nodes (see Figure 5).

2. In this second step the lack of space continuity that may have originated in the previous step is fixed. The traffic demand segments that belong to the same inter-ring traffic demand but have not chosen the same crossconnect-node must be *rearranged* to provide space continuity, i.e., the crossconnect-node of one of the two segments must be changed. Notice that such rearrangement affects the value of the loads on links $(R1_{(N1-1)}, R1_{N1})$ and $(R2_{(N2-1)}, R2_{N2})$. Let $p = l_{max1} - l_{(R1_{(N1-1)},R1_{N1})}$ and $q = l_{max2} - l_{(R2_{(N2-1)},R2_{N2})}$ be the unused capacity on the links between the crossconnect-nodes for ring $R1$ and $R2$, respectively. Two cases are possible.

   - The available capacity $p+q$ suffices to rearrange the traffic demand segments that do not satisfy the space continuity (without increasing the value of l_{max1} and l_{max2}). In this case a modified version of the INDES algorithm is run on ring Rv in order to minimize the crossconnect-node unbalance factor δ_{xc} without increasing the number of wavelengths needed in each ring.
   - The available capacity $p+q$ does not suffice to rearrange the traffic demand segments that do not satisfy the space continuity. In this case the traffic balancing already determined for one of the rings is considered final, whereas the traffic balancing of

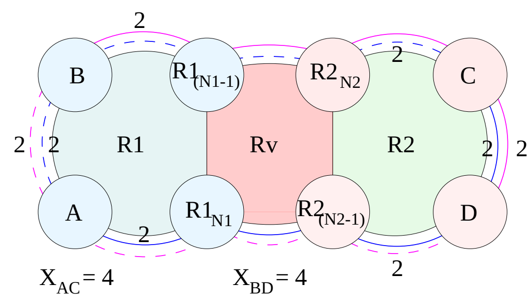


Figure 6. OBF algorithm splitting technique

the other ring is recomputed in order to guarantee space continuity of the inter-ring traffic demands. The ring for which the traffic balancing is recomputed is the one with more unused capacity on the link that connects the crossconnect-nodes, i.e., if $(p > q)$ then $R1$ is re-balanced, else $R2$ is re-balanced. This choice is based on the intuition that the ring with more unused capacity on that link more likely yields a recomputed traffic balancing that does not increase the overall number of wavelengths.

3.2. Crossconnect Balancing First (OBF) Algorithm

This algorithm first balances the inter-ring traffic over the two crossconnect-nodes, thus it minimizes the crossconnect-node unbalance factor, δ_{xc}. Then, it minimizes the load on the most congested link, l_{max1} and l_{max2}, on both rings.

To achieve this goal, the inter-ring traffic demands are split: half of the inter-ring traffic demands are divided into two intra-ring traffic demand segments and are initially routed using:

- in $R1$, the links along the clockwise path from the end-node to crossconnect-node $R1_{(N1-1)}$
- in $R2$, the links along the clockwise path from crossconnect-node $R2_{N2}$ to the end-node.

The other half of inter-ring demands divided into two intra-ring traffic demand segments and are initially routed using:

- in $R1$, the links along the clockwise path from crossconnect-node $R1_{N1}$ to the end-node
- in $R2$, the links along the clockwise path from the end-node to crossconnect-node $R2_{N2-1}$.

This choice assigns half of the inter-ring traffic demands to each crossconnect-node (Figure 6). The crossconnect for each inter-ring lightpath is therefore determined and the INDES load balancing algorithm can be applied to each ring individually.

4. NUMERICAL RESULTS

This section presents some results obtained using two benchmark networks to assess the performance of both the LBF and the OBF algorithm. To assess the performance of both algorithms a number of experiments are run under various traffic conditions. For each network set up, the three matrices that characterize the traffic, I^1, I^2, and X, are randomly generated. It is assumed that no traffic demands are generated between the two crossconnect-nodes. The traffic pattern is characterized by parameters $0 \leq r_1 \leq 1$ and $0 \leq r_2 \leq 1$, defined as follows:

$$r_1 = \frac{\sum_{i \in N1} \sum_{j \in N2} X_{ij}}{\sum_{i \in N1} \sum_{j \in N1 \ j \neq i} I^1_{i,j} + \sum_{i \in N1} \sum_{j \in N2} X_{ij}} \tag{1}$$

$$r_2 = \frac{\sum_{i \in N2} \sum_{j \in N1} X_{ij}}{\sum_{i \in N2} \sum_{j \in N2 \ j \neq i} I^1_{i,j} + \sum_{i \in N2} \sum_{j \in N1} X_{ij}} \tag{2}$$

The values of r_1 and r_2 represent the ratio between the number of inter-ring lightpaths and the total number of lightpaths routed through ring $R1$ and ring $R2$, respectively. Due to the symmetry of the traffic demands, the numerators in equations 1 and 2 are equal. A value of r_1 (r_2) close to zero indicates that the traffic in ring $R1$ ($R2$) is dominated by intra-ring traffic. A value of r_1 (r_2) close to one, indicates that the traffic in ring $R1$ ($R2$) is dominated by inter-ring traffic.

Parameters of interest are l_{max1}, l_{max2} — the number of wavelengths required to carry the working lightpaths in ring $R1$ and ring $R2$, respectively — and δ_{xc}. Plots report the expected value of such parameters obtained when r_1 and r_2 are assigned values within specific ranges.

4.1. Benchmark Network 1

Benchmark network 1 (BN1) consists of two dual-interconnected WDM rings. Each ring comprises five nodes. The relatively small size of the network, makes it possible to exhaustively search for the optimal solution in terms of l_{max1} and l_{max2} within reasonable computational time. Figure 7(a) shows[¶] $E[l_{max1}]$ versus r_1. Results show that the proposed algorithms perform well when compared to the exhaustive search.

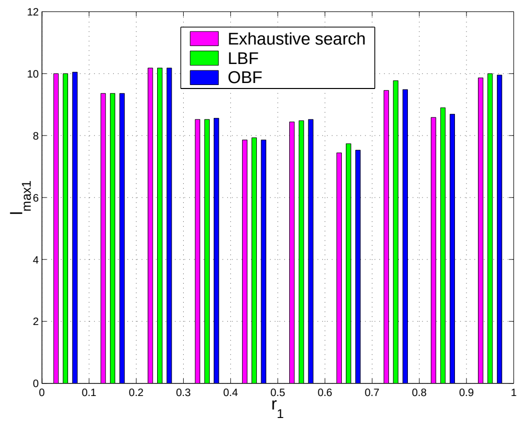
4.2. Benchmark Network 2

Benchmark network 2 (BN2) consists of two dual-interconnected WDM rings, each ring connecting 9 nodes. In this case, the exhaustive search is already impractical.

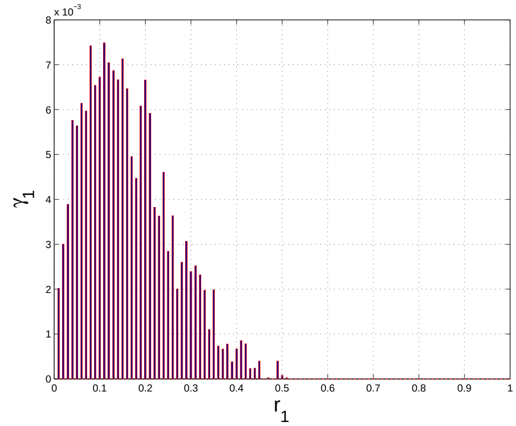
A fair comparison of the two proposed algorithms under various traffic patterns is carried out using the following parameters:

$$\gamma_1 = \frac{\left(l^{OBF}_{max1} - l^{LBF}_{max1}\right)}{\left(\sum_{(i,j) \in L1} l1_{(i,j)} / |N1|\right)} \tag{3}$$

[¶]Similar results can be found for $E[l_{max2}]$ on ring $R2$



(a) Average value of l_{max1} versus r_1 in BN1



(b) Ring R1: average value of γ_1 versus r_1 in BN2

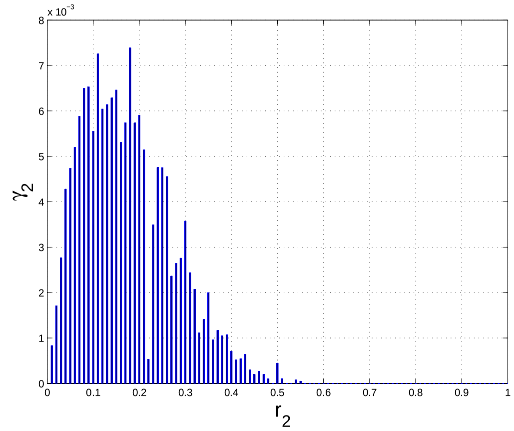
$$\gamma_2 = \frac{\left(l_{max2}^{OBF} - l_{max2}^{LBF}\right)}{\left(\sum_{(i,j)\in L2} l2_{(i,j)}/|N2|\right)} \tag{4}$$

where:

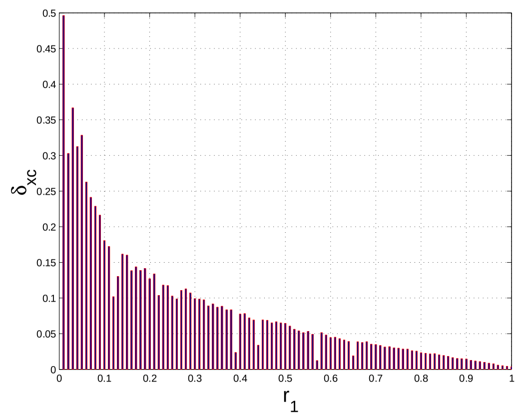
- $l1_{(i,j)}$: number of wavelengths provisioned on link $(i,j) \in L1$, in case shortest path[9] routing is used
- $l2_{(i,j)}$: number of wavelengths provisioned on link $(i,j) \in L2$, in case shortest path routing is used
- l_{max1}^{OBF} (l_{max2}^{OBF}): l_{max1} (l_{max2}) obtained using the OBF algorithm
- l_{max1}^{LBF} (l_{max2}^{LBF}): l_{max1} (l_{max2}) obtained using the LBF algorithm.

Values γ_1 and γ_2 are proportional to the additional wavelength costs per link incurred when the OBF algorithm is used instead of the LBF algorithm, normalized to the average cost per link obtained with shortest path routing.

In Figure 7(b), the range of values for r_1 is divided into 100 intervals. For each interval Δ_i a number of random traffic demands are generated such that the resulting $r_1 \in \Delta_i$. The plotted histogram shows the average value of γ_1 for each interval Δ_i. Figure 7(c) shows the same plot for γ_2. The plots show that when the traffic is dominated by one traffic type only, i.e., either mostly inter-ring traffic or mostly intra-ring traffic, the difference between the two algorithms in terms of required wavelengths is negligible. Some performance difference is visible when the traffic is a combination of both traffic types.



(c) Ring $R2$: average value of γ_1 versus r_1 in BN2



(d) Algorithm LBF: average value of δ_{xc} versus r_1 in BN2

In Figure 7(d), a procedure similar to the one used to obtain the plots in Figure 7(b), is used to derive the average value of δ_{xc} over a number of experiments. These values are obtained running the LBF algorithm. The outcome of the OBF algorithm is not represented here as it always yields an even distribution of inter-ring lightpaths over the crossconnect-nodes. The plot shows that the LBF algorithm well balances the distribution of inter-ring lightpaths over two crossconnect-nodes, when the traffic is dominated by inter-ring traffic. In presence of intra-ring lightpaths, the distribution of inter-ring lightpaths over the two crossconnect-nodes obtained by the LBF algorithm is not balanced at all.

5. CONCLUSION

This paper dealt with the problem of optimally designing a WDM network with dual-ring and dual-crossconnect architecture. The problem was studied under two design scenarios: optimize the crossconnect-node unbalance factor prior to or after minimizing the link load parameters, l_{max1} and l_{max2}. Two polynomial time algorithms were proposed to solve the optimization problems, yielding numerical results that are few percent worse than the optimal solution.

The study assessed the impact of the traffic distribution on the performance of the proposed algorithms. When the traffic is dominated by inter-ring traffic both algorithms yield similar optimal results, in terms of both link load and crossconnect-node unbalance factor. When the traffic is mixed but dominated by intra-ring traffic, the choice of the preferred design algorithm is determined by the cost factor that is more critical.

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