Dimensioning all-optical dual-homing hierarchical multi-ring networks with various connectivities

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Abstract

This paper presents a dimensioning approach tailored to hierarchical dual-homing multi-ring architectures with and without wavelength converters. Analytical lower bounds based on cutsets are applied in order to allocate the traffic to the individual rings efficiently, as well as to estimate the number of required fibres per ring. The use of these bounds also facilitates the evaluation of the proposed methods. The effect of using a hierarchical fibre distribution, which allocates a larger number of fibres in more heavily loaded rings, is studied. Further, the impact of topology and network connectivity on wavelength and hardware requirements is investigated considering various multi-ring topologies.

1 Introduction

Large-scale networks consisting of interconnected rings constitute promising structures, since they combine several intrinsic ring advantages, such as fast and simple routing and restoration, and also overcome the capacity limitations of rings when considering large numbers of nodes. In particular, wavelength division multiplexing (WDM) rings are attractive for upgrading their electronic counterparts. However, bi-connectivity is a critical consideration in the design of all-optical highly-survivable topologies. Regarding multi-ring networks, this implies dual-homing structures, *i.e.* each ring should share at least two nodes with other ring(s). Thus, the focus is on hierarchical multi-ring structures, where the network nodes are partitioned into several rings according to traffic patterns, which are then interconnected by sharing two common nodes with higher-level ring(s).

Numerous heuristics deal with routing and wavelength allocation in arbitrary mesh or single rings, both without and with wavelength conversion [1], corresponding to the cases of wavelength-path (WP) routing and virtual WP (VWP) routing respectively. However, only [2, 3] have addressed multi-ring networks. In these clustered structures, additional issues need to be considered in order to achieve cost-effective design which include: (i) even traffic distribution within rings to minimise the maximum load, and hence, the network wavelength requirement (NWR), *i.e.* the number of distinct wavelengths required; and

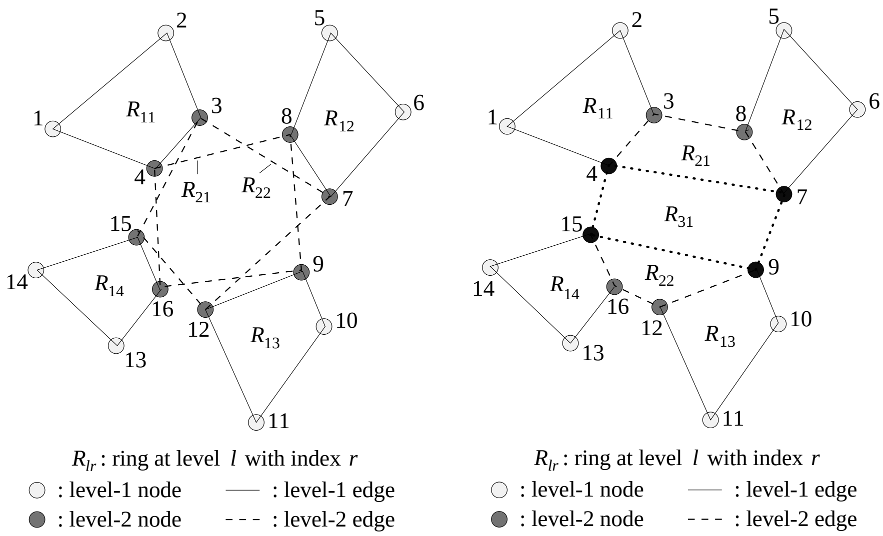
(ii) minimising the inter-ring traffic, in order to reduce the complexity of the hardware at interconnecting nodes and to simplify network management [4].

A *distribute load & allocate* (DLA) dimensioning approach tailored to dual-homing rings is employed here, aiming to capture these issues. Cutset-based analytical lower bounds are applied in order to allocate the traffic to the individual rings efficiently, as well as to estimate the number of required fibres per ring. In terms of the objective function used, DLA was shown in [3] to outperform an earlier heuristic for arbitrary topologies and give values close to the optimum obtained by integer linear programming. However, in contrast to [2, 3] that consider *uniform fibre distribution* (UFD), this paper focuses on networks with *hierarchical fibre distribution* (HFD), where a larger number of fibres is allocated to rings with heavier traffic load. The quality of results is assessed against a cutset-based analytical lower bound for NWR. Empirical results are also reported comparing various topologies, in terms of NWR, switching and transmission capacity as a function of connectivity.

2 Dual-homing multi-ring networks

The focus is on hierarchical bi-connected multi-ring networks (see *e.g.* Fig. 1(a) and (b)) designed using the *partition, construct & perturb* method [5]. Consider a network with levels l, $1 \leq l \leq L$, having an arbitrary set of nodes n, partitioned into rings at $l = 1$. To route traffic between rings, two common nodes are selected from each, and connected via edges e, either existing or new, to form rings at the level $l + 1$. The process continues, building into a hierarchical structure.

Two interconnection schemes can be used [4], depending on the placement of the two common nodes in level $l + 1$. The first, *same common ring* (SCR), selects two adjacent common nodes and includes them, plus the edge between them, in the next level ring. The second, *different common ring* (DCR), selects a pair of common nodes, not necessarily adjacent, and includes them in different rings at level $l + 1$.



(a) DCR

(b) SCR

Figure 1: Hierarchical ring interconnection schemes

3 Cutset-based lower bounds

To estimate lower bounds on NWR for given numbers of fibres on each edge, a cutset-based analytical approach is employed [3] based on network topology information.

Consider a network represented by a graph G. A cutset of a connected graph G is a minimal set of edges of such that its removal from G disconnects the graph. A lower bound to NWR, $c_{w,\min}$, can be determined by the maximum load on any cutset edge. However, the number of all possible cutsets increases significantly with the number of nodes, c_n, rendering the estimate of $c_{w,\min}$ difficult. A more efficient estimate of $c_{w,\min}$ is provided by concentrating on the most heavily-loaded cutsets.

Consequently, this paper follows [3] in focusing on single and multi-ring networks. In a single ring, only cutsets with two edges are considered. However, in multi-ring networks, the focus is on cutsets that divide the set of rings at each level $l < L$ into two subsets. These cutsets correspond to the edges that connect different rings (*interconnecting cutsets*), which tend to be more heavily loaded due to inter-ring traffic. In addition, the cutsets that separate the common nodes (and any nodes directly between them) from the rest of nodes in each lower-level ring (*base-level cutsets*) are considered, as they are likely to be the most heavily loaded within each individual lower-level ring.

4 Hierarchical fibre distribution

Most work has focused on networks with fixed number of fibres per edge [1, 2, 3]. However, traffic is not evenly distributed in a network, resulting in high NWR requirements due to few heavily loaded edges. To address this issue, a simple method for hierarchical fibre distribution (HFD) based on cutsets is employed here. Given a total allowed number of fibres, it assigns all fibres by applying the following procedure iteratively. First, it allocates a single fibre on all the network edges. Next, considering every ring in the network, one at a time, from the highest level down, an additional fibre is provisionally added to each edge of the ring. If this results in an improvement in the current cutset NWR bound, the fibres are retained. After every individual ring has been checked, if there has been no improvement, then every level is considered, an entire level at a time, from the highest down, with an additional fibre provisionally added to each edge. If this also fails, then all edges of the network are tried. After any success, the overall process restarts, with high-level individual rings again being considered. For instance, in Fig. 1(a), the procedure begins by trying to add fibres to each ring, starting from R_{21}, then R_{22}, R_{11}, and so on, and then finally R_{14}. If this fails, it attempts to add fibres to both second level rings R_{21} and R_{22} at the same time. Finally, if there has been no success so far, it tries adding a fibre to all edges.

5 Dual-homing dimensioning methods

A DLA dimensioning approach has been developed for both VWP and WP, aiming to minimise the number of rings traversed rather than the number of hops. The objective is to minimise the path cost in order to reduce hardware cost in terms of switching ports, while keeping the NWR minimum. A cost ρ_p is assigned to each path, given by $\rho_p = \alpha_1 h_p + \alpha_2 r_p$, where h_p and r_p denote the number of hops and rings traversed, while α_1 and α_2 are constants ($\alpha_1 << \alpha_2$).

First, similarly to [3], the possible ring paths for each node pair are determined, *i.e.* the ring sequence traversed by a path, consisting of up to $2L - 1$ rings if the end nodes belong to different rings, or just one otherwise. Next, the ring path that minimises the maximum traffic load on any of rings traversed, is selected. This is obtained using the cutset-based bound on each ring. Finally, depending on whether wavelength conversion is available or not, VWP or WP routing is adopted.

DLA-VWP. In the VWP scheme, use of wavelength converters is assumed. The objective is to evenly distribute the traffic on the individual rings, while keeping the number of hops in each ring minimum. For simplicity, each ring is considered separately and the traffic is routed on the lowest-hop path. Then, perturbations to the routing are performed in an attempt to reduce the maximum load or to find lower-hop paths.

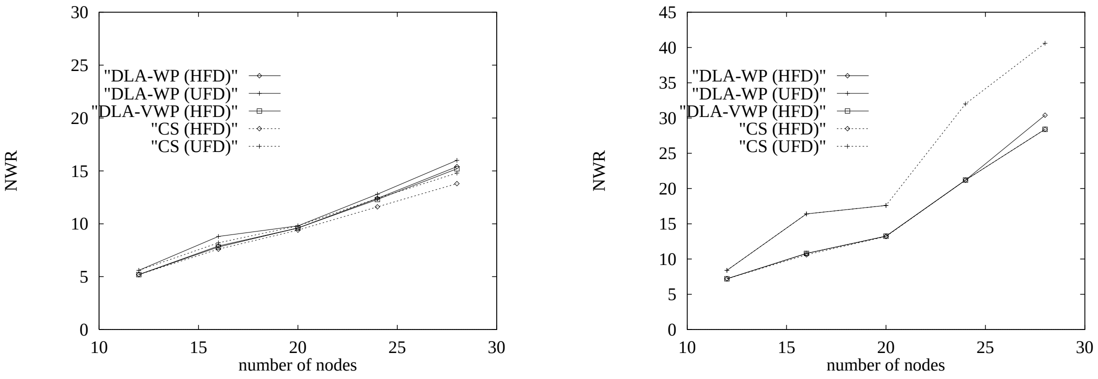
DLA-WP. In this case, the same wavelength is assigned to all the edges that constitute a path. First, all node pairs are sorted into hop-count descending order considering their lowest hop path candidate. All the inter-ring node pairs are considered prior to intra-ring node pairs. Then, a lower bound on the expected NWR w_{lim} is estimated by employing cutsets on each ring. The path-wavelength combination with the lower cost connecting a node pair s-d is selected among all possible candidates for a given ring path, provided there is a free wavelength available on that path with index $w < w_{\text{lim}}$, trying to keep the resulting NWR value below w_{lim}. If there is no such path, the path with the lowest indexed free wavelength is selected. Finally, perturbations to the routing and re-arrangements of the wavelengths are performed to further reduce the NWR or the path costs.

6 Experimental results

Wavelength and switch-port requirements have been obtained for both SCR and DCR multi-ring networks with $c_n = 12, 16, 20, 24, 28$, and a maximum allowed number of nodes per ring $c_{n_r} = 4, 6$ for $\alpha_1 = 1$, $\alpha_2 = 100$. Five network design problems were used for each pair of c_n, c_{n_r} (*i.e.* 100 networks in total), where the node locations and traffic requirements were generated with the same method as those employed in [3]. Each network uses a 1000 km $\times$ 1000 km area, carries an overall traffic of $10 \cdot c_n$ Gb/s, employs multiple fibre edges, and has a traffic granularity of 2.5 Gb/s.

DLA has been compared with cutset lower bounds in terms of NWR for both DCR and SCR networks using HFD, as well as UFD (Fig. 2(a) and (b)). A notable reduction in NWR can be observed in SCR networks with HFD compared to those with UFD, due to the higher number of fibres in heavily loaded edges. Overall, the results here indicate that there is no substantial benefit when wavelength conversion is used. However, using DLA-WP with HFD to compare topologies with different interconnection schemes (Fig. 3(a) and (b)), there is a notable difference in both the objective function values and NWR, with DCR clearly performing better than SCR for both. Moreover, results from [3] indicate that DCR achieves a more balanced ring interconnection in terms of capacity, and therefore wavelengths and switching capacity, as the inter-ring traffic burden is more evenly distributed. Further, in SCR some edges are heavily loaded, and consequently, the network is more vulnerable to failure(s). For both SCR and DCR, the number of common node ports decreases, while the NWR and the total number of switch ports increases, as c_{n_r} increases. This can be explained by the corresponding decrease in the number of rings and edges in the network, which leads to the aggregation of the switching capacity in larger nodes.

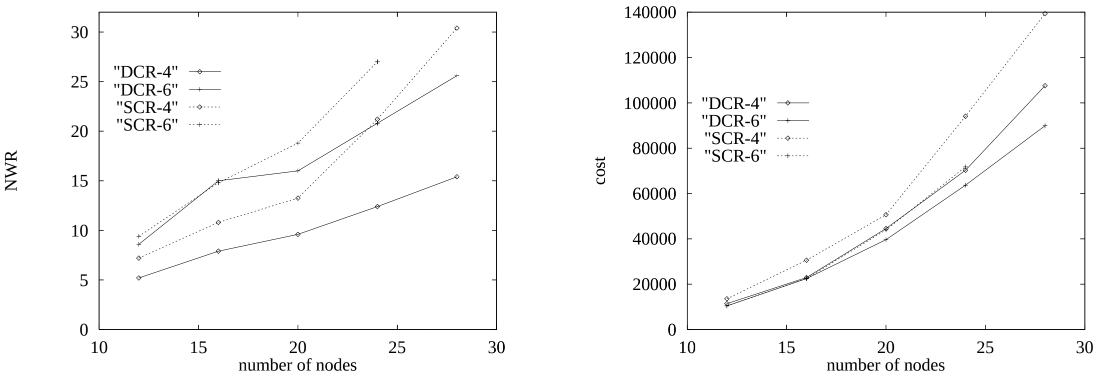
In order to examine the impact of connectivity on NWR, a simple metric which depends on the sparsity of network edges is employed similar to that adopted in [6] for arbitrary mesh topologies. It considers the ratio of total number of fibres to that in a fully-meshed network with the same average number of fibres, in contrast to [6] that fo-



(a) DCR

(b) SCR

Figure 2: Average NWR for DCR and SCR, $c_{n_r} = 4$



(a) NWR

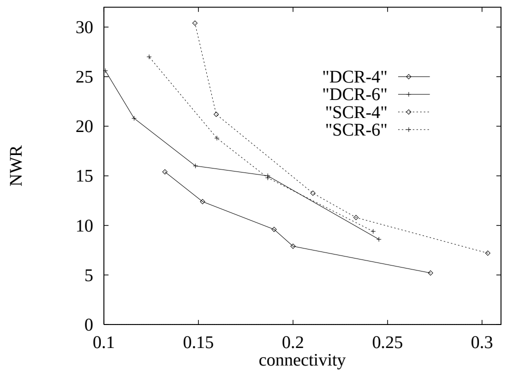
(b) cost

Figure 3: Average results for DCR and SCR, $c_{n_r} = 4, 6$ using HFD

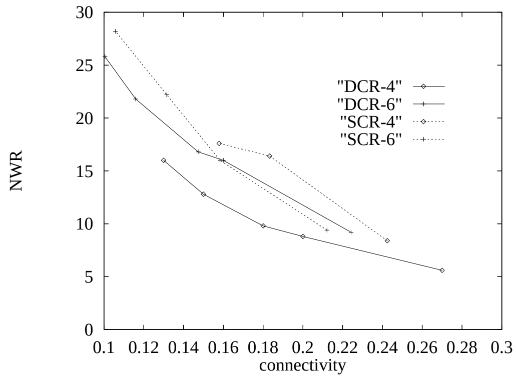
cuses on the corresponding ratio of edges. Considering DCR and SCR topologies, NWR results for varying connectivity are presented in Fig. 4(a) and (b) using both HFD and UFD. As in [6], NWR decreases as the connectivity increases. This is expected since in a network with larger number of edges and fibres, the traffic is distributed more evenly, resulting in lower NWR. However, it can be observed that NWR greatly depends on the interconnection scheme. In particular, considering the same connectivity value, DCR requires less wavelengths than SCR. This becomes even more obvious as the connectivity, and consequently the number of edges and fibres in the network, decreases. In both HFD and UFD cases, SCR sparsely-connected topologies end up with a high NWR, due to some higher-level heavily-loaded edges.

7 Conclusions

The problem of dimensioning large-scale WDM networks employing multiple interconnected rings has been considered. Dimensioning methods tailored to clustered optical topologies have been described. In particular, cutset-based bounds have been used to allocate the traffic to the individual rings, as well as to hierarchically distribute fibres in the network in order to provide more capacity in heavily-loaded edges. The latter leads



(a) HFD



(b) UFD

Figure 4: Average NWR for DCR and SCR, $c_{n_r} = 4, 6$

to a reduction in NWR compared to a uniform fibre allocation, which also depends on the ring interconnection scheme adopted. Overall, results indicate that both topology and network connectivity represent critical factors for both the wavelength and hardware requirements.

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