Wavelength routing in all-optical dual-homing hierarchical multi-ring networks

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Abstract. The design of large-scale networks adopting a clustered-based approach, in particular interconnection of multiple sub-networks, combined with wavelength division multiplexing technology, promises scalable and expandable structures. This paper focuses on wavelength-path routing in resilient hierarchical multi-ring architectures. A novel dimensioning approach is presented, where the path selection depends mainly on the number of rings traversed, aiming to keep the wavelength requirement minimum, while reducing the network hardware cost in terms of switching ports. Cutset-based analytical lower bounds tailored to multi-ring networks are employed to facilitate evaluation of the proposed method. Empirical results obtained for structures adopting different interconnection schemes reveal that the topology is a critical factor for both the wavelength and hardware requirements.

1. Introduction

The design of large-scale networks employing a cluster-based approach (interconnection of multiple sub-networks), combined with the use of wavelength division multiplexing (WDM) technology, promises to achieve scalable and expandable structures. WDM rings constitute suitable sub-networks, increasingly considered for deployment in various network scenarios, due to the recent advances in add/drop multiplexing ring equipment, and also their fast, simple routing and restoration. Also, future networks should survive the most likely failure scenarios, as the fibres used will carry huge amounts of traffic. Thus, bi-connectivity is a critical consideration in the design of all-optical topologies for high survivability. In particular, for multi-ring networks, this implies dual-homing structures, *i.e.* each ring should share at least two nodes with other ring(s). This paper concentrates on hierarchical multi-ring networks, where the nodes are partitioned into several rings according to existing communities of interest, which are then interconnected with higher-level ring(s).

In a WDM network without wavelength converters, individual wavelength channels must use the same wavelength end-to-end (wavelength-path routing), whereas wavelength conversion removes this constraint (virtual-wavelength-path routing). Numerous heuristics deal with routing and wavelength allocation in arbitrary mesh or single rings, both with and without wavelength conversion [1]–[4]. However, to the best of our knowledge, no prior work has considered routing and wavelength allocation in multi-ring networks, as has also been observed in [1]. In these clustered structures, additional issues need to be considered in order to achieve cost-effective design. First, the traffic should be evenly distributed within rings to minimise the maximum load, and hence, the network wavelength requirement (NWR), *i.e.* the number of distinct wavelengths required. Secondly, in order to minimise the complexity of the hardware employed at interconnecting nodes, and to simplify the network management, the inter-ring traffic should also be minimised.

Thus, in this paper, a novel approach is adopted for wavelength-path (WP) routing which minimises the number of rings traversed rather than the number of hops, in contrast to methods employing only k-shortest path [2] or k-lowest hop count routing [3]. The overall objective is to keep the NWR as low as possible, while reducing the network hardware cost in terms of switching ports. The results are assessed against a cutset-based analytical lower bound for NWR. In addition, a WP routing heuristic for arbitrary mesh networks [3] is used for comparison. Furthermore, the dimensioning method is applied to various topologies using different interconnection schemes, in contrast to [4] which only compares networks with different numbers of edges. Results indicate that the interconnection scheme adopted is a critical factor for both the wavelength and hardware requirements.

The paper is organised as follows: Section 2 briefly describes the multi-ring architectures studied. Section 3 presents the WP dimensioning method, while Section 4 focuses on cutset-based lower bounds. Section 5 discusses the results and reports a comparison between networks adopting different interconnection strategies. Finally, Section 6 records conclusions and suggestions for future work.

2. Hierarchical dual-homing multi-ring networks

This paper focuses on hierarchical bi-connected multi-ring networks. 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. In order to connect any pair of network nodes at most $(2L - 1)$ rings need to be traversed [5].

Two interconnection schemes are examined [5], which depend 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 $l + 1$.

3. Wavelength-path routing in multi-ring networks

A dual-homing dimensioning method has been developed for WP routing (DH-WP), is depicted in the flowchart of Fig. 1 and can be described as follows.

Step 1: *Find possible paths for each node pair.* For source-destination (s-d) pairs that belong to the same ring, only two distinct paths p_{sd} and p'_{sd} are considered, corresponding to the two opposite ring directions. Whereas only ring sequences consisting of up to $2L - 1$ rings are considered, if s and d belong to different rings. Consider the local common nodes of s and d, $c_1(s)$, $c_2(s)$, and $c_1(d)$, $c_2(d)$ respectively, which

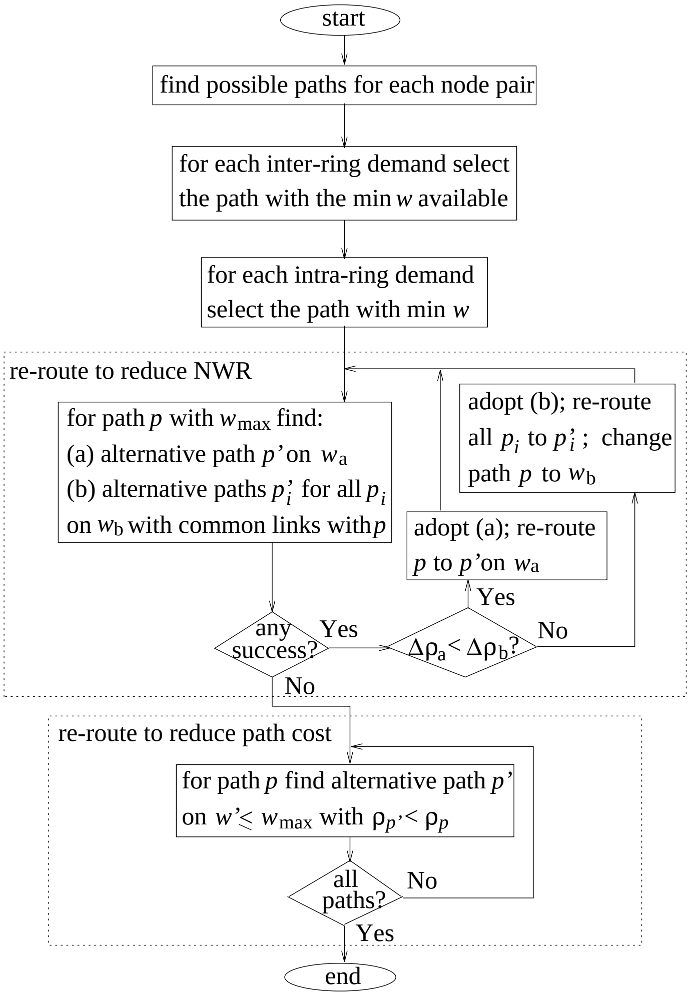


Figure 1: Dual-homing wavelength-path routing flowchart.

connect the local ring of s or d to a higher-level ring. Then, check whether there is a higher-level interconnecting ring between any combination of these. If such a ring does not exist, the same process is repeated at the next level until an interconnecting ring is found. Thus, an inherently hierarchical approach to routing is adopted, reflecting the structure of the networks themselves.

Consider a ring sequence of $r \leq 2L - 1$ rings connecting s-d. This corresponds to 2^r paths for all the combinations of clockwise and counter-clockwise directions of each ring. To illustrate, in Fig. 2(b) the node pair (2, 11) can be connected by selecting between two ring sequences $\{R_{11}, R_{21}, R_{13}\}$ and $\{R_{11}, R_{22}, R_{13}\}$, each corresponding to eight distinct paths.

Step 2: *Inter-ring traffic demands.* In multi-ring networks priority is given to connections which traverse more than one ring, since they correspond to a larger number of hops and therefore are more difficult to establish. Let ρ_p denote the cost of path p, given by:

$$\rho_p = \alpha_1 h_p + \alpha_2 r_p, \quad \alpha_1 << \alpha_2 \tag{1}$$

where α_1 and α_2 are constants, and h_p, r_p are the number of hops and rings traversed by path p respectively. The path cost function reflects the switch-port requirements, since the number of common-node ports depends linearly on the number of rings traversed, while the number of ring-node ports depends on the path hop count [5]. Wavelengths are assigned following a *first-fit* approach. In particular, the path connecting s-d with the lowest indexed wavelength free is selected. If there is more than one candidate path, the one with the lowest cost is selected.

Step 3: *Intra-ring traffic demands.* In this case, only two paths are considered since routing is restricted to one ring. As before, the path with the lower indexed free wavelength is selected. If both the complementary paths have free capacity on that wavelength, the one with the lower hop count is selected.

Step 4: *Re-route to reduce NWR.* Perturbations to the routing and re-arrangements of the wavelengths are performed to further reduce the NWR. An operation similar to that described in [2] is used, tailored to multi-ring networks. Consider the path p with the highest wavelength number $w_{\max}$. Two operations are performed: (a) it is checked if p can be re-routed to another path p', connecting the same node pair, at a lower wavelength $w_a < w_{\max}$. The difference in the costs is $\Delta\rho_a = \rho_{p'} - \rho_p$. (b) An attempt is made to change the wavelength of path p to $w_b < w_{\max}$, by re-routing all the paths that already occupy w_b and share at least one edge with p. If p traverses k edges, up to k paths p_i, $i = 1, \ldots, k$ would need to be re-routed to paths p_i'. The difference in costs is $\Delta\rho_b = \sum_{i=1}^{k} \rho_{p_i'} - \rho_{p_i}$. If neither of these two operations leads to improved results, the algorithm moves to the next step, otherwise the operation that leads to the lower cost difference is adopted, and step 4 repeated.

Step 5: *Re-route to reduce path cost.* Given the highest wavelength $w_{\max}$ in the network, each path p is replaced in turn with a lower-cost path p' on a wavelength $w' \leq w_{\max}$. The aim is to reduce the cost of each path without increasing the NWR.

4. Cutset-based lower bounds

To estimate lower bounds for NWR, a cutset-based analytical approach is employed; this was previously described in [6], where it was applied to small arbitrary networks.

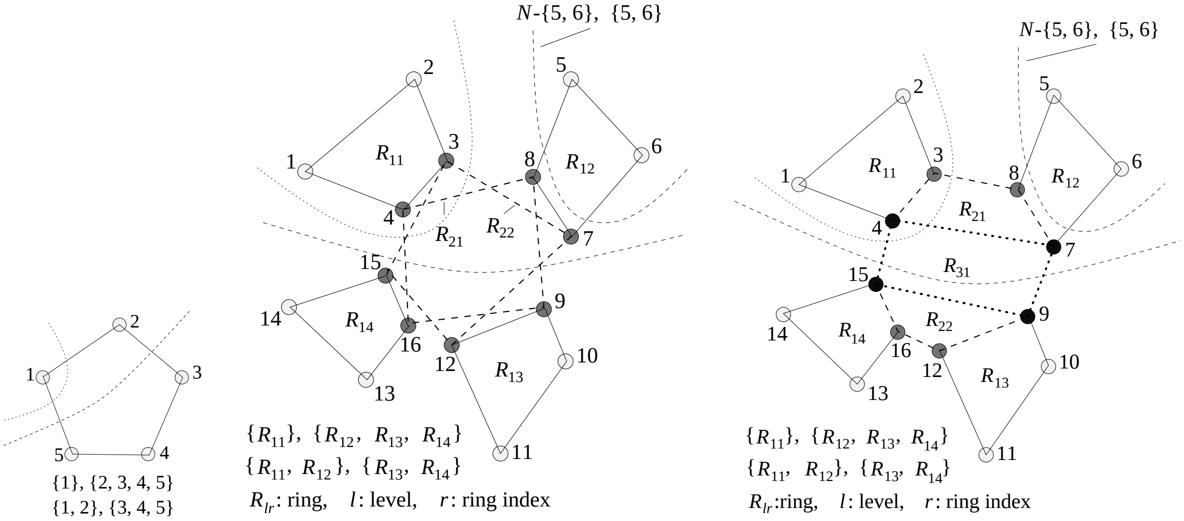
Consider a network represented by an undirected graph $G(N, E)$ where N, E are the sets of nodes and edges respectively. Let c_n and c_e denote the cardinalities of the sets N, E. The network graph $G(N, E)$ is divided into two sub-graphs $G_1(N_1, E_1)$ and $G_2(N_2, E_2)$ by removing a set of edges, E_c, called a cutset of size c_{e_c}. The removed edges are such that the network graph becomes disconnected and $N_1 \cap N_2 = \emptyset$, $N_1 \cup N_2 = N$, $E_1 \cap E_2 = \emptyset$ and $E_1 \cup E_2 \cup E_c = E$. It is apparent that all the paths connecting nodes that belong to different sub-graphs will traverse an edge that belongs to E_c. As a result, a lower bound to NWR, $c_{w,\min}$, can be determined by the maximum load on any cutset edge, and given by:

$$c_{w,\min} = max\{\lceil \sum_{n_1 \in N_1} \sum_{n_2 \in N_2} t'_{n_1,n_2} / f_{e_c} \rceil\}, \qquad \forall E_c \in E \tag{2}$$

where f_e is the number of fibres on edge e, and $f_{e_c} = \sum_{e \in E_c} f_e$ is the total number of fibres on the cutset edges. However, the number of all possible cutsets ε in a graph is given by:

$$\varepsilon = \sum_{c_{n_1}=1}^{\lfloor c_n/2 \rfloor} \frac{c_n!}{c_{n_1}!(c_n - c_{n_1})!} \tag{3}$$

and increases significantly with c_n, rendering the estimate $c_{w,\min}$ difficult. A more efficient estimate of $c_{w,\min}$ is provided by concentrating on the most heavily-loaded cutsets. These cutsets should correspond to small values of c_{e_c}, or alternatively to almost equally-sized N_1, N_2. However, in order to find them in large networks, computationally-intensive graph-theory algorithms would be required.



(a) Ring (b) DCR (c) SCR

Figure 2: Example cutsets

Consequently, building on the approach in [6], this paper instead focuses on single and multi-ring networks. In a single ring, Eqn. 2 is applied considering only those cutsets with $c_{e_c} = 2$. The number of two-edge cutsets is $\varepsilon' = c_n \cdot \lfloor c_n/2 \rfloor$, since there are c_n cutsets with $c_{e_c} = 2$ that split the ring into c_{n_1} and $c_n - c_{n_1}$ nodes for each value of $c_{n_1} = 1, \ldots, \lfloor c_n/2 \rfloor$. Two examples of these are given in Fig. 2(a), where the cutsets are denoted by lines bisecting the ring, and the corresponding node sets indicated at the bottom of the figure.

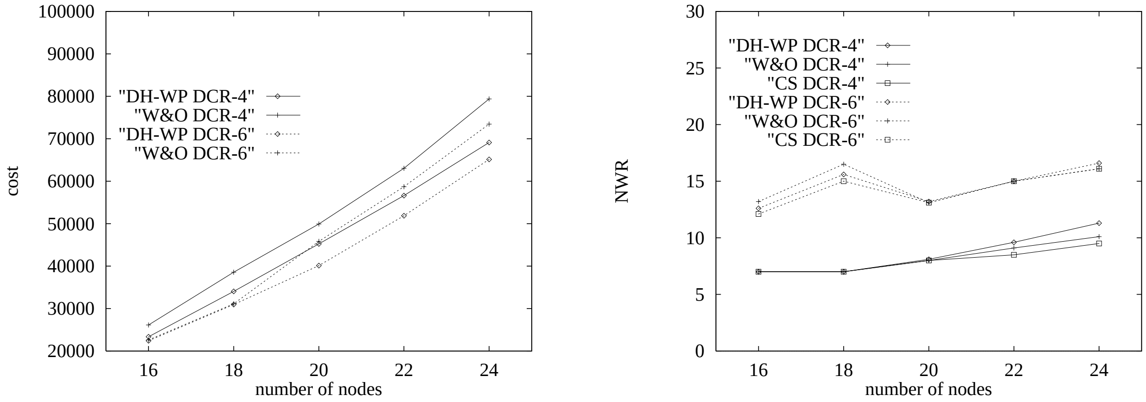
In the case of multi-ring networks, the focus is on cutsets that divide the set of rings at each level $l < L$ into two sub-sets. These cutsets correspond to the edges that connect different rings, which tend to be more heavily loaded due to inter-ring traffic. Therefore, instead of examining all the combinations of nodes (Eqn. 3), all the possible combinations of rings at each level are considered. 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 are also considered. These cutsets are likely to be the most heavily loaded within each individual lower-level ring. Given the number of rings at level l, c_{r_l}, Eqn. 3 becomes:

$$\varepsilon' = \sum_{l=1}^{L-1} \sum_{c_x=1}^{\lfloor c_{r_l}/2 \rfloor} \frac{c_{r_l}!}{c_x!(c_{r_l} - c_x)!} + c_{r_1} \tag{4}$$

Clearly, ε' is far smaller than ε in a non-trivial network. Examples of possible cutsets on multi-ring architectures, dividing rings at $l = 1$, are depicted in Fig. 2(b) and (c), where the cutsets are again denoted by both lines and ring sets. A cutset separating the common nodes of ring R_{12} from the rest of its nodes is also shown in each of these figures.

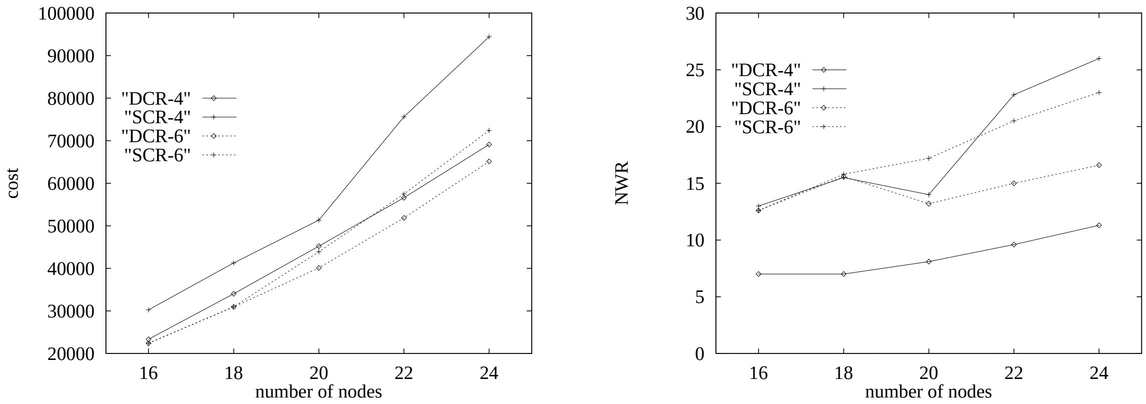
5. Experimental results

Wavelength and switch-port requirements have been obtained for multi-ring networks with $c_n = 16, 18, 20, 22, 24$. A case study for a 20-node European network [7] is also



(a) cost (b) NWR

Figure 3: Average multi-ring results employing DCR, $c_{n_r} = 4, 6$, $f_e = 5$



(a) cost (b) NWR

Figure 4: Average multi-ring results for DCR and SCR, $c_{n_r} = 4, 6$, $f_e = 5$

provided to illustrate the general dimensioning procedure.

Ten network design problems were used for each value of c_n, (*i.e.* 50 networks in total). The node locations and traffic requirements for these were generated using the method described in [8], although further modified to ensure reasonable node separations. Each network uses a 1000 km $\times$ 1000 km area, carries an overall traffic of $10 \cdot c_n$ Gb/s and employs multiple fibre edges, while the traffic granularity (*i.e.* the bit rate of each wavelength channel) is considered to be 2.5 Gb/s. The methods were implemented as an extension to NOMaD [9].

Multi-ring networks. DH-WP has been compared with both cutset lower bounds and an alternative WP heuristic (W&O WP) for arbitrary mesh networks [3]. The latter was shown to give good results against other heuristics in [10]. Considering DCR with maximum allowed number of nodes per ring $c_{n_r} = 4, 6$, results have been obtained for both objective function values (*i.e.* the sum of all path costs) and NWR for $\alpha_1 = 1$, $\alpha_2 = 100$ (Fig. 3(a) and (b)). In terms of the objective function values, DH-WP results outperform those obtained with W&O WP. With respect to NWR, there is no obvious winner between DH-WP and W&O WP. DH-WP may lead to slightly higher values than W&O WP in few cases, as a consequence of not choosing paths with minimum

Table 1: Results for the EON employing SCR and DCR

c_{n_r}	L	c_r	c_e		$c_{w,\min}$		DH-WP c_w		Switch ports		CN ports	
			SCR	DCR	SCR	DCR	SCR	DCR	SCR	DCR	SCR	DCR
4	3	10	30	34	16	9	16	10	4464	4232	964	906
6	2	6	25	28	21	16	21	17	5156	4592	816	744
8	2	4	23	23	24	24	24	24	5552	5552	728	728

hop count. However, this is outweighted by the significant reduction in the number of rings traversed, resulting in less switching ports in common nodes and simpler network management. In all cases, WP NWR values are close to the cutset lower bounds. These bounds provide a metric for the maximum load on a link and ignore the wavelength continuity. Therefore, these results indicate that no substantial benefit is to be expected with the use of wavelength conversion for the static traffic matrices considered here.

However, using DH-WP to compare topologies with different interconnection schemes (Fig. 4(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. 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 more heavily loaded, and consequently, the network is more vulnerable to failure(s).

European optical network case study. A 20-node network design problem [7], with the network required to carry the traffic between the main centres of Europe, is used to illustrate the application of the two aforementioned interconnection schemes to a realistic network scenario. The traffic matrix employed is an estimate of future traffic demands modelled in [11]. Results have been obtained with cutsets and DH-WP for NWR, switch ports, and common-node ports, for different values of $c_{n_r} = 4, 6, 8$ for both SCR and DCR with $f_e = 4$ (Table 1). The number of levels, rings and edges for the various networks are also recorded.

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 links in the network, which leads to the aggregation of the switching capacity in larger nodes. In addition, DCR gives in all cases better results than SCR for both the wavelength and switch-port requirements, with the exception of $c_{n_r} = 8$ where both schemes result in the same network.

6. Conclusions & further work

The problem of wavelength-path routing and wavelength allocation in large-scale WDM networks employing multiple interconnected rings has been considered. A novel dimensioning method (DH-WP) tailored to optical clustered topologies has been described, which aims to minimise both wavelength and switch-port requirements, the latter depending in turn on the number of rings traversed and the hop counts of the network paths. Results indicate a notable improvement in the switch-port requirements over an heuristic for arbitrary mesh networks. In terms of the NWR, DH-WP gives values close to the estimated cutset lower bounds. However, there is a remarkable difference in both wavelength and switch-port requirements when comparing different bi-connected interconnection schemes.

Currently, the use of full and sparse wavelength conversion is under investigation. Dimensioning networks using different numbers of fibres per edge with the use of a more complex objective function is also being considered.

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