p-cycle Protection in Wavelength Routed Networks

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Abstract The concept of p-cycle protection (PCP) in virtual wavelength path (VWP) networks and the integer linear programming (ILP) approach are revisited. The specific problems in wavelength path (WP) networks in connection with (PCP) are discussed. The wavelength allocation (WA) schema has a significant impact on the capacity performance of PCP. A heuristic for joint WA and p-cycle search (PCS) is presented. The performance of the developed algorithm is investigated using a case study for a Pan-European network.

1. Introduction

Actual optical transport networks are mostly based on rings. Rings are easy to manage and offer a fast way for protection switching. Unfortunately, they are rather capacity inefficient and require for the usual kind of rings, e.g. Dedicated Protection Switched Rings (DPRings), often more than twice the working capacity for protection [Arijs et al., 2000].

Mesh based networks require much less spare capacity, but have the drawback of complicated protection mechanisms. The protection may be based on paths (End to End) or on spans. Sharing of the spare resources for protection often requires a complicated signaling and therefore takes much longer than the simple switching in the case of rings.

Therefore, several new protection techniques for the transition of ring networks towards mesh based networks, are discussed [Grover et al., 2002]. A very promising one, the concept of p-cycles (preconfigured protection cycles), has been introduced by Grover and Stamatelakis [Grover and Stamatelakis, 1998]. Here, the spare capacity for span protection is organized in cycles and shared among the on-cycle links and the straddling links of the cycle. In this way, a redundancy of as low as $34\,\%$ for protection is achieved [Grover and Doucette, 2002] while retaining the speed of rings.

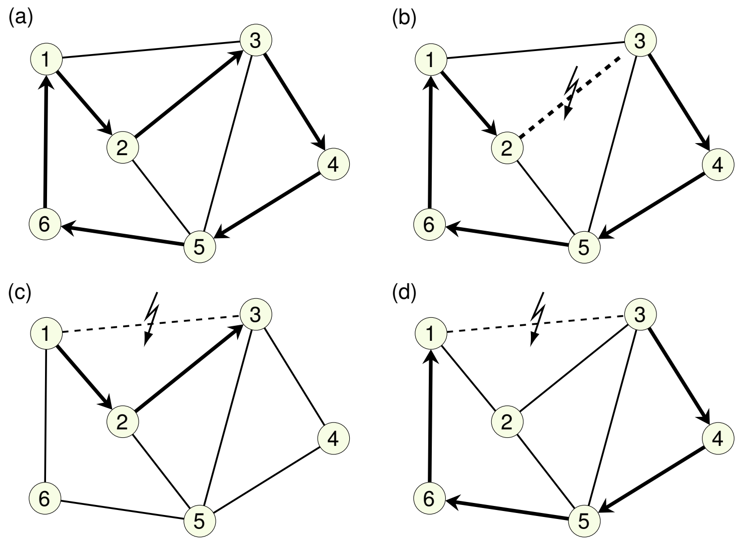

Figure 1. Sample network with p-cycle protection.

To replace costly electronic by cheap optical devices, it has been proposed to introduce an optical path (OP) layer [Sato et al., 1994]. Routing of optical channels is realized in the optical domain by wavelength routing. Such a path is called wavelength path (WP) if the wavelength is not changed. When the nodes have the capability of wavelength conversion, one gets a virtual wavelength path (VWP).

Schupke *et. al* formulated in case of VWP the determination of the optimal p-cycle set as an Integer Linear Program (ILP) [Schupke et al., 2002]. For WP networks, the configuration with multiple fibers per span are examined. In that way, wavelength blocking did not occur. As will be shown, the chosen wavelength allocation (WA) has a significant impact on the required capacity in case of a single pair of fibers per span.

In this work, a simple heuristic for the joint WA and the search of the p-cycles (p-cycle search, PCS) in case of WP is investigated. The structure of the paper is as follows. First the concept of the p-cycles and the problems arising in WP networks are explained. Techniques for the planning for VWP are discussed. A heuristic for the jointed WA and PCS in case of WP is presented. The results of the algorithm for Pan-European Networks ([Batchelor et al., 2000] and [De Maesschalck et al., 2003]) are analyzed. The short summary at the end includes an outlook for further work.

network	*nodes*	*edges*	*mean degree*
BT	28	41	2.93
RT	28	34	2.43
TT	28	60	4.29
COST 239	11	22	4.00

Table 1. General figures of the investigated networks.

2. Span protection with p-cycles

In Fig. 1(a), a simple network with an established p-cycle is shown (bold lines). Here and in the following, p-cycles are always directed. When one of the links on the cycle fails, similar to a ring with multiplex-section protection, all wavelengths on the span are redirected in the reverse direction around the cycle. This is shown for a connection from node 3 to node 2 in (b). The reverse connection may not be protected by this cycle.

In addition to this, in a p-cycle, the straddling links of the cycle benefit from the protection of the cycle as well. In case of a failure, the traffic of a connection from node 1 to node 3 may be rerouted as in (c) and for the reverse link as in (d).

Due to the sharing of the spare resources by several links, the efficiency may be close to mesh protection.

Here and in the following, only link failures are covered, the occurrence of (rare) node failure is neglected. OP networks are circuit-switched networks with a switching granularity of one wavelength.

In this paper, the p-cycles are assumed to be identified in advance during the network planning phase and established by the network management system. Here, similar techniques as for the ring identification may be used [Arijs et al., 2000]. The self-organization of p-cycles is not a topic of this article.

The possible cycles may be constructed by a branch-first strategy [Reingold et al., 1977]. Starting from a node, the neighbors are recursively visited until one returns to the start node. When all cycles, which belongs to the start node are found, the node and its connecting edges are removed from the network. The process is repeated with a new start node. This way, all cycles of the network are determined.

As an example, the topologies for a Pan-European transport network of the action COST 266 as defined in [De Maesschalck et al., 2003] and the network of action COST 239 [Batchelor et al., 2000] are used. Table 1 shows the general figures of these networks. Here, BT (Basic topology), RT (Ring Topology) and TT (Triangular Topology) refer to networks with the same node

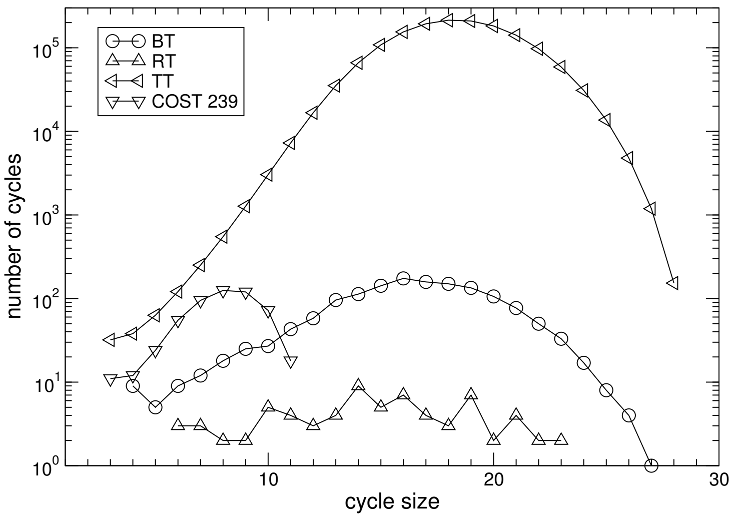

Figure 2. Number of cycles in dependence of cycle size.

set, but different number of links and therefore different mean degree (number of edges divided by number of nodes). In Fig. 2 the number of cycles in dependence on the size of the cycle is depicted. Note, that only simple cycles are counted, which have no nodal crossing (the cycle passes a node more than once)).

As can be seen, the higher the mean degree of the network, the more cycles exist. Especially for the TT network, the number of cycles tends to explode. Therefore it is necessary to restrict the search among the most promising candidates [Grover and Doucette, 2002].

3. PCP for VWP case

The normal approach for the planning of a network protected by p-cycles is as follows. The working paths are routed through the network. Among a set of all possible p-cycles, the optimal subset has to be chosen. The objective is to minimize the required spare capacity. All connections on the spans of the network have to be protected.

To gain optimum from the capacity savings of p-cycles, the routing of the working paths has to be chosen properly. Here, a simple approach is to perform load balancing [Schupke et al., 2002]. A better way is to do the routing and the PCS jointly [Grover and Doucette, 2002]. This may be formulated as an ILP for the graph $G = (V, E)$ with nodes set V and edges set E:

$$\text{Objective:} \qquad \min\left(\sum_{j=1}^{|P|} m_j \cdot l(p_j) + \sum_{j=1}^{|W|} n_j \cdot l(w_j)\right) \tag{1a}$$

under the constraints

$$\sum_{j=1}^{|W|} n_j \cdot \Phi_{\alpha,j} = D_\alpha \qquad \forall \alpha \in V \times V \tag{1b}$$

$$\sum_{j=1}^{|P|} m_j \cdot \Psi_{i,j} \geq \sum_{j=1}^{|W|} n_j \cdot \Gamma_{i,j} \qquad \forall i \in E \tag{1c}$$

$$n_j, m_j \in \mathbb{N}_0 \quad \forall j \tag{1d}$$

Here, P and W are the set of p-cycles and working paths candidates, respectively. The optimization variables are m_j, the number of p-cycle j, and n_j, the number of connection routed along path j. The length of the p-cycle and the working path in terms of hops are denoted by $l(p_j)$ and $l(w_j)$, respectively. The coefficient $\Psi_{i,j} \in \{0, 1\}$ indicates if the p-cycle j protects edge i. Similar, $\Gamma_{i,j} \in \{0, 1\}$ determines, if working path j uses the edge i. To determine, if demand D_α of the traffic matrix between the node pair $\alpha = (v_1, v_2)$ may be carried by the working path j, the variable $\Phi_{\alpha,j} \in \{0, 1\}$ has been introduced. Here, $\Phi_{\alpha,j} = 1$ when the start node of path j is v_1 and its end node v_2.

The objective is to find the optimal set of the variables m_j, n_j which minimize the total required capacity of the network as formulated in (1a). The constraint (1b) ensures that every request of the traffic matrix is routed. By (1c) it is determined, if there is enough spare capacity available to protect all connections which use edge i.

In total, there are $k \cdot (|V| \cdot (|V| - 1)) + |P|$ variables for the problem, with k the number of path candidates for the routing of every node-pair. For a network of the order of 30 nodes, this results in $1000 - 10000$ integer variables, which may be solved within $0.2\,\%$ of optimality with the ILP solver software CPLEX in less than a minute on a Sun Blade 100 machine.

With several available paths for a node-pair α, it is possible to perform an asymmetric routing. This means, that when $\bar{p_j}$ is the reverse path to the path p_j from v_2 to v_1 and $\bar{m_j}$ is the corresponding variable, then it is not necessarily $m_j = \bar{m_j}$. It turns out, that the additional constraint of a symmetric routing (which drastically reduces the number of variables to $k \cdot (|V| \cdot (|V| - 1))/2 + |P|$) results in almost no penalty.

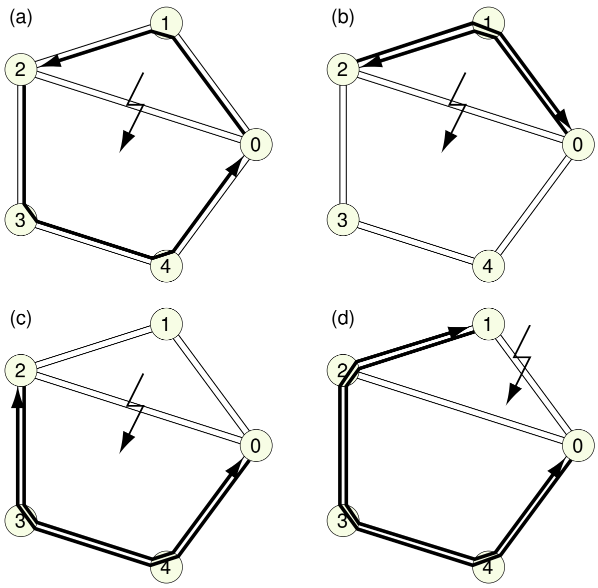

Figure 3. Equal wavelength assignment of forward and reverse path.

4. Problems in WP networks with p-cycle protection

Since in WP routed networks, the nodes have no capabilities for wavelength conversion, sharing of protection capacity may only occur among connections of the same wavelength. Wavelength blocking of the p-cycles and the working paths has to be avoided. In the WP case study of Schupke *et al.* [Schupke et al., 2002] wavelength blocking of the p-cycles does not occur due to multiple fibers. Thus, the problem may be separated in sub-problems, one for each wavelength (but without the ability to perform joint routing and PCS).

When there is only a single pair of fibers per span available, the wavelength allocation scheme has a crucial impact on the performance of the p-cycle protection (PCP).

A wavelength which is used on a link for working traffic blocks a p-cycle on the same link and wavelength. Sharing is only possible among several p-cycles (the network is designed for single link failure only). The situation will be explained in more detail in Fig. 3, which shows a part of a network.

A symmetric routing for a duplex-connection is assumed (for every path, there is a reverse path in the other direction) with the same wavelength assigned to both directions. Therefore, the spans are symmetrically loaded and both directions of a specific wavelength are used for a span. Here, a straddling link

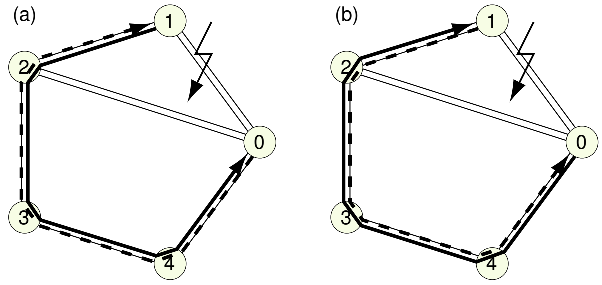

Figure 4. Different wavelengths for forward and reverse path.

may be protected by one uni-directional p-cycle (a) or by a part of two p-cycles (b and c).

For a on-cycle link, the situation is worse (d). Here the only possibility is to use a part of two p-cycles. The drawn cycle may not be used as a p-cycle in neither direction, since the wavelength is blocked by the working span. If Fig. 3 present the whole network, no protection using p-cycles would be possible.

This means that sharing is essentially only possible among straddling links under this symmetry assumption. Therefore normally the performance for WP is much worse than for VWP networks.

To avoid this, it is more favorable to use a wavelength only in one direction of a span (at least for the links which lies on the p-cycle). This results in different wavelengths for the two directions of a connection. Thus, protection and sharing is now possible with e.g. two p-cycles, one for each wavelength and direction, as shown in Fig. 4.

These problems are similar to those which arise in Shared Protection Rings (SPRings) in a two fiber configuration. A way to circumvent them is to use two pairs of fibers instead of just one.

For a single pair, the wavelength allocation scheme has a significant impact on the performance of the PCP scheme. Therefore, it would be the best solution, to include the WA in the ILP formulation of Eq. 1. This would require $|L|$ times more variables, when L is the set of available wavelengths. For usual problem sizes, this makes the ILP approach impossible. Therefore, in the next section, a simple heuristic for joint wavelength assignment and PCS is introduced.

5. Heuristic for WA and PCS

Three sub-problems for WP networks with PCP may be distinguished:

1 Routing of the paths,

2 Wavelength assignment and

3 p-cycle search.

Unfortunately, each of these sub-problems depends on the two other. For the VWP case, the second one is irrelevant. Therefore an ILP approach is successful.

For the proposed heuristic the determined ILP-solution of the VWP-case is used to derive a solution for the WP case. Thus, the penalty for WP may be estimated as well. The approach is as follows.

1 Solve the ILP problem for the VWP case.

2 Take the resulting routing of the solution and sort the paths according to their lengths (in term of hops). Paths are directed.

3 Start with the first wavelength.

4 Test if one of the paths (starting at the longest) may use this wavelength. Otherwise look at the next wavelength.

5 Assign the wavelength to the path. Add p-cycles for all edges of the path, which are up to now unprotected for that color.

6 Proceed to step 4 until every path is colored (and protected).

A path may be only assigned to a wavelength, when the wavelength is not used on all its edges and when it is possible to protect all edges for that wavelength with the given set of p-cycles. When a p-cycle is added for a wavelength, the wavelength may not be in use on its edges by a working path. The wavelength is blocked on the spans by working-paths in further steps. There is no limit of the maximal number of wavelengths on a link.

As a heuristic in step 5, the p-cycle which protects the highest number of unprotected edges and, among them, that with the highest score $s(p_j) = \mathrm{TS}(p_j)$ is being successively added. Here, TS is the topological score

$$\mathrm{TS}(p_j) = \sum_{i \in E} \Psi_{i,j}, \tag{2}$$

as introduced by [Grover and Doucette, 2002].

Two approaches have been investigated for the set of p-cycles among which the algorithm makes a choice. The first one is to use all cycles which are in agreement with the boundary conditions (e.g. max. number of nodes or max. cycle length in fiber kilometers). The second set covers those, which are used by the VWP solution.

This heuristic of wavelength filling is very similar to the "First-Fit" assignment of wavelengths (which has proved to perform well [Harai et al., 1998]).

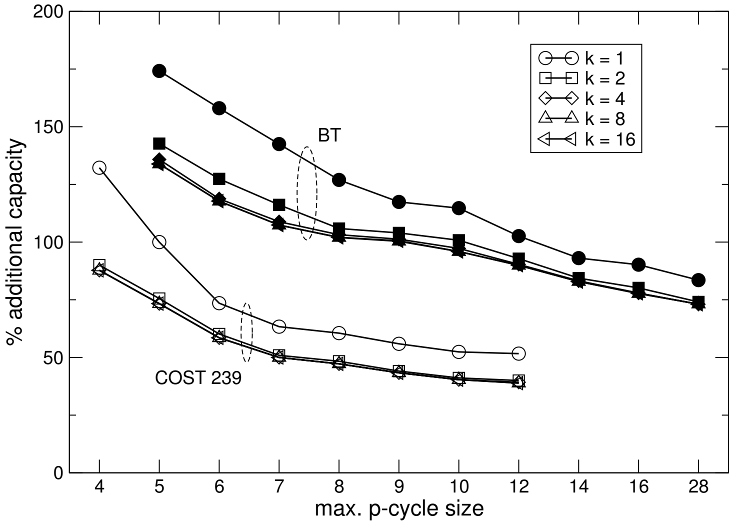

Figure 5. Required spare capacity in dependence of max. cycle size in VWP case.

For high traffic load, there may be a large number of wavelengths required. Then, it would be better to allow more than one pair of fibers between the network nodes and use the approach of Schupke [Schupke et al., 2002] for the PCS.

6. Case-study for Pan-European Transport Network

The computation of the cycles for a given topology has been implemented in C++ using the C++ library LEDA [Mehlhorn and Näher, 1999]. After completion, the equations (1) are automatically generated. The ILP problem for the VWP case is solved with CPLEX 7.0. Here, a time limit of $30\,\mathrm{min}$ has been set. The heuristic for the WP case is implemented in C++ and LEDA, again.

The usual running time of the algorithm is negligible (excluding that of the ILP solver). A solution for the ILP problem is normally found very quickly (less than a minute), but CPLEX may guarantee optimality only up to $0.2\,\%$ for the larger networks.

In Fig. 5, the required additional capacity for protection with p-cycles in dependence of the max. p-cycle size (in terms of number of nodes) in the VWP-case is depicted. The capacity is normalized to the required capacity for shortest path routing of the working paths. Here, the additional capacity is defined as the spare capacity for the p-cycles plus the additional capacity for the working paths, when the shortest path is not being used.

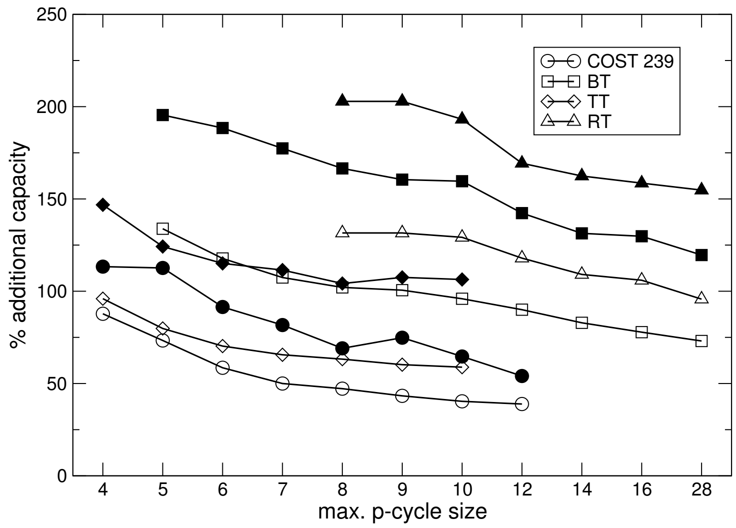

Figure 6. Comparision of VWP and WP solution.

For the optimization of the routing, the k shortest paths with $k = 1, 2, 4, 8, 16$ for every node pair α have been used. Here, $k = 1$ corresponds to shortest path routing.

For the highly meshed COST 239 network, only $38\,\%$ of additional capacity is required for PCP, when there is no limit in the max. size of the cycles. With cycles of max. 7 nodes, $50\,\%$ additional capacity is necessary. It is sufficient, to investigate only the 4 shortest paths for every node-pair, there is no further improvement with more path candidates.

For the sparser and larger BT network, at least $73\,\%$ capacity is needed for PCP and this may only be achieved with large cycles. The investigations have been performed for the total traffic of year 2002. For realistic max. cycle sizes of 8 nodes, approximately a doubling of the network capacity is needed.

In Fig. 6, the VWP case (empty symbols) and the WP case (filled symbols) for all investigated networks are shown. Here, the solution with the minimal required capacity among runs with different k and both sets (p-cycles of VWP solution and all allowed cycles) of possible p-cycles for the WP case has been taken. Because the heuristic gradually fills the wavelengths with the paths and established p-cycles, it sometimes performs slightly better with less cycles or a different routing. The variation among the solutions is rather small.

For the TT case, only a max. cycle size of up to 10 has been examined, because here the number of cycles explodes for larger ones (and as a result the number of variables of the ILP problem). Therefore, one should limit the search among the most promising cycles [Grover and Doucette, 2002]. For the RT, the minimum cycle for which a solution exists size is 8.

In general, due to the wavelength continuity constraints, the WP case requires between $40\,\%$ and $60\,\%$ additional resources. This is because sharing of protection resources may only occur among paths with the same wavelength. The higher the mean degree of the network, the lower will be this penalty.

A granularity of STM 16 (Synchronous Transfer Mode) per wavelength has been assumed. Transmission impairment (which limits e.g. the max. length of a WP path) has been neglected. There are only marginal changes for a granularity of STM 64 channels.

7. Conclusions and Outlook

The problems of p-cycle protection in wavelength path networks has been discussed. It has been shown that it is of crucial importance to do the wavelength assignment and the p-cycle search jointly to benefit the most from the capacity savings of p-cycles in WP-networks. A simple and fast heuristic for joint p-cycle search and path coloring has been proposed. The performance of the algorithm has been tested for case studies of Pan-European networks.

For p-cycle protection with a single pair of fibers, wavelength conversion seems to significantly save spare capacity due to the better sharing of the protection resources. This is especially true for on-cycle spans. Therefore, a partial wavelength conversion capability may be of interest.

It would be possible to optimize the solution with a meta heuristic, e.g. Simulated Annealing (routing, wavelength assignment and p-cycle search).

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