Allocation of Spare Capacity for Shared Protection of Optical Paths in Transport Networks

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Abstract— **The planning of capacity for shared protection is investigated. After recapitulation of the different protection schemes, the similarities between wavelength-allocation for light-paths and the sharing of network resources for protection is discussed. The concept of a protection sharing group (PSG) is introduced and an efficient algorithm to form PSG is presented. A heuristic approach to route the paths of a PSG is discussed. Using case studies for rings and a Pan-European network, the performance of the presented algorithms is evaluated.**

Keywords— **Shared Protection, All-Optical-Networks, Wavelength-Allocation, Optical-Path, Graph-Coloring**

I. Introduction

WAVELENGTH-DIVISION multiplexing (WDM) is used to an increasing extent for point-to-point connections in wide area networks to satisfy the demand for transport capacity and to cope with the tremendous demand in bandwidth. SDH (Synchronous Digital Hierarchy) or SONET (Synchronous Optical Network) represent the classic transport protocol. But also, ATM (Asynchronous Transfer Mode), IP (Internet Protocol) or PDH (Plesiochronous Digital Hierarchy) are present in the actual transport network. Therefore, it has been proposed to introduce an optical path (OP) layer [1]. Routing of optical channels is realized in the optical domain by wavelength routing. The transmission capacity of each optical fiber is steadily extended due to the utilization of WDM and high-speed time division multiplexing (TDM) techniques. In case of a failure, a huge amount of traffic is hit. Therefore, high availability of the connections is mandatory and protection is an important design issue for the optical layer.

The network should be at least immune against a single failure. Different protection schemes may be used. Often, every working path (WP) has a dedicated protection (DP) path. In case of a failure, the traffic is switched to the protection path (PP). In that way, low reaction times can be achieved but at least twice the transport capacity in terms of the actual transported traffic is necessary. This may be avoided when several working paths share common protection capacity. This is referred as shared protection (SP) and needs much less spare capacity in the network. The problems for the planning of the spare capacity for SP are twofold:

- which WP may share protection resources, and
- the dimensioning of the needed spare capacity.

In this work, an algorithm to deal with both problems for the OP is presented.

The outline of the paper is as following. First, the different protection schemes are explained. Then, the assignment of channels to wavelengths and its mapping to a graph coloring problem is discussed. In the next section the implications for forming protection share groups (PSG) is discussed. A heuristic algorithm to minimize the needed spare capacity for a PSG is presented. Case studies for rings of different sizes and the Pan-European Network of the COST 239 action are used as examples, which allow to compare the necessary spare capacity for dedicated and shared protection. A short summary at the end includes an outlook for further work.

II. Protection Schemes

Normally, the transport network consists of several layers, and mutual independence of these layers is aspired. But this also means that each layer can have its own network protection system. Its optimization should be in terms of resource utilization and restoration time.

Possible network protection schemes in terms of the switching unit are listed according to [2] in the order of decreasing granularity:

- optical multiplex section (OMS) protection in the OMS layer,
- OP protection/restoration in the OP layer,
- Multiplex Section (MS) protection in the SDH MS layer,
- HOP (SDH: higher order path) protection/restoration in the SDH HOP layer, and
- Virtual Path (VP) protection/restoration in the ATM VP layer.

Here, especially the advent of optical switches for the optical cross-connects (OXC) makes it possible, to realize the first two schemes which imply the reconfiguration of the optical layer in order to restore the light-paths in the case of failures.

While e.g. for an ATM network with up to $2^{12} = 4096$ VP per fiber may need to be restored, a number of wavelengths from 32 up to 192 per fiber yields an appropriate degree for restoration granularity [2].

Another criterion is whether the protection resources are dedicated or shared. For DP or $1+1$ protection, the traffic may be directed along both paths simultaneously. In case of signal loss due to a failure, the end-node may switch to the other path without the need for signaling. On the other hand, in case of SP or $1:N$ protection, N WP share the spare resources for protection. Therefore, signaling is necessary to reestablish the connection.

A multi-layer scheme requires a tremendous amount of spare resources. For $1+1$ protection $100\,\%$ spare resources are required, which are doubled with each additional layer.

Therefore, a three-layer protection scheme needs 400 % additional resources in the network. SP in general needs less resources than DP.

Generally, in ring architectures, the handling of the protection path for a given working path is simple (its just the other way round in the ring), but may result in very long protection paths. On the other hand, mesh architectures offer much more flexibility but have the drawback of increased planning complexity due to the high degrees of freedom, especially when using SP.

Protection activation should be a fast process, and has to take place in less than 50 ms to prevent service disruption. In contrary to that, restoration, that means finding a connection under the given actual network state, is slow and in general, an interruption of the service is experienced by the user.

In this paper, SP for OP is investigated. An algorithm is presented that enables to identify the OP which may share the protection capacity and to set it up. In case of disruption of an OP, the OXC are reconfigured according to a configuration computed in advance. The objective is to minimize the needed spare capacity for protection under the constraint to be immune against a single failure. Here, two failure cases are distinguished:

- link failure e.g. due to a fiber break or a damaged inline-amplifier
- node failure e.g. due to the breakdown of an OXC.

Other failure scenarios like the simultaneous outage of several fibers by a cable break are not treated.

III. Wavelength Assignment and Graph Coloring

One of the steps in the design of a WDM network is the assignment of OP to wavelengths. The objective is to minimize the number of used wavelengths while avoiding wavelength blocking: two OP which share a common fiber have to use different wavelengths.

The wavelength allocation may be carried out jointly with the routing of the channels e.g. using the layered graph method [3]. In that way, it is possible to incorporate boundary conditions like the maximum number of wavelengths in a fiber or to take into account the capability of wavelength conversion of some network nodes.

Another approach is to first route the OP on the given network topology and then to assign the wavelengths. This leads normally to sub-optimum solutions but significantly reduces the complexity especially when a great number of paths have to be established.

Like most other problems in graph theory, the wavelength allocation problem is NP-complete. Therefore quite a few heuristics exist e.g. first-fit, mostly-used, longer path first [4] to give good results with low computational effort.

In [5], it has been shown by B. Mikac et. al, that for given WP $wp_1, \ldots, wp_n$, the problem may be mapped to the graph coloring problem. For that, the wavelength coloring graph (WCG) G_{wc} is constructed where every node wp_i represents a WP. Two nodes wp_i and wp_j are connected by an edge if they share a common link or a fiber in the original network. In that case, it is necessary to assign a different wavelength to each path. Therefore, coloring the nodes of G_{wc} with two adjacent nodes having different colors is equivalent to the wavelength assignment problem of the WP.

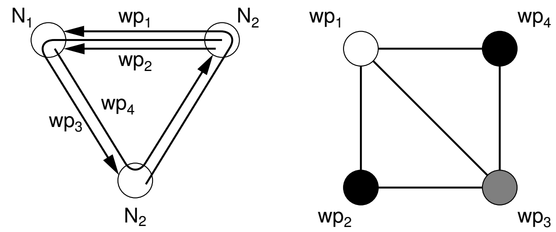

Fig. 1. Simple network on the left and its WCG G_{wc} on the right hand side.

In Fig. 1 an example of a simple network consisting of three network nodes and four established OP is depicted. On the right hand side the corresponding WCG is shown. In total, three wavelengths are necessary for the realization.

Graph-coloring is an actual research topic of discrete mathematics. A simple heuristic to color the nodes of G_{wc} is operating as follows:

- start with an uncolored graph, enumerate the available colors c_i,
- assign the color c_i to the uncolored node with the highest degree ,
- assign the color c_i to all nodes which have no neighbors with this color,
- the same procedure is performed with the next color c_{i+1} until all nodes are colored.

The computational complexity is proportional to the square of the number of nodes in G_{wc}. It has been shown in [5], that the heuristic for graph coloring has a better performance than the heuristic first-fit or most-used in terms of the number of used wavelengths. This is due to the fact, that the algorithm has more knowledge about the problem and is therefore better adapted, but has the drawback, that wavelength conversion is not considered.

To color the WCG of Fig. 1, one starts with color c_1 for node wp_1. Since all nodes are adjacent to wp_1, the color cannot not be reused. Then, node wp_3 gets color c_2. When assigning c_3 to wp_2, this color may also be taken for wp_4 because both nodes are not neighbors.

IV. Algorithm for allocation of shared capacity

In a WDM system, a fiber break results in a failure of multiple wavelength channels. Therefore, two channels which share a common fiber may not share a protection channel. Two WP which do not fail simultaneously by a failure in the network are denoted as mutual independent. This is strongly related to the investigated type of failure. If e.g. only link failures are considered, two WP which share a common node are mutually independent whereas this is not true, when also node failures are taken into account.

The planning of spare capacity for given WP may be divided in two steps:

- forming of set of paths which may share protection resources, in the following referred as PSG (Protection Share Group), and
- set-up and allocation of the needed spare resources for one PSG.

It is assumed, that the routing for the WP has been carried out in advance, and also that for each WP, one wavelength (without wavelength conversion) has been assigned.

A. Forming of PSG

The problem of forming PSG is very similar to wavelength allocation. The working paths are represented in the graph G_{sg}, where each path is mapped to a vertex and two vertices are connected by an edge, when they are mutual dependent and may not share protection resources. When only single link failures are investigated, the graph G_{sg} is equivalent to the graph G_{wc}, which has been used in the last section for the wavelength allocation. Therefore, all WP which have been assigned the same wavelength may also share protection capacity and form a PSG. In that way, the problem complexity is reduced.

When in addition node failures are considered, G_{sg} contains additional edges compared to G_{wc} to take the possibility of a simultaneous breakdown of two OP by one node failure into account. The same is true when a cable break affects several fibers at a time. Nevertheless, the heuristic of coloring this graph to form PSG may still be applied with the objective to minimize the number of used colors or accordingly that of PSG. The further treatment remains the same, although the resulting "colors" are no longer related to wavelengths. In the same way, also multiple failure scenarios may be incorporated or the method may be applied, when wavelength conversion for the WP has been used.

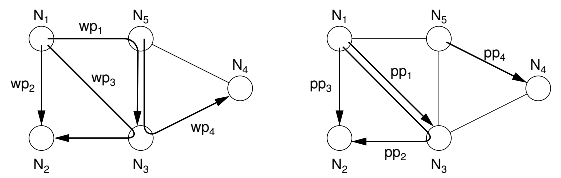

Fig. 2. Network with some WP (left hand side) and corresponding PP (right hand side).

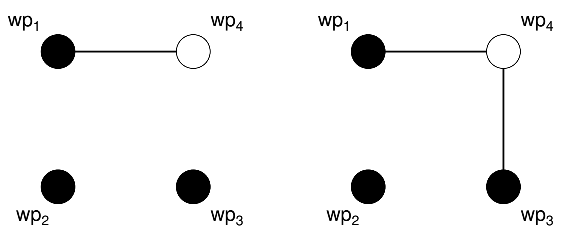

Fig. 3. Example for forming a PSG using the graph coloring method for the case of LF (left hand side) and LF + NF (right hand side).

In Fig. 2 on the left hand side, an example network with some of the chosen WP is depicted. On the right hand side, the corresponding PP are shown. To form the PSG, every of the four paths is transformed into a node in G_{sg}, which is shown in Fig. 3. When only link failures (LF) are investigated, wp_1 and wp_4 are mutually dependent, because they share the link between N_5 and N_3. Coloring the graph with the explained heuristic results in two PSG as shown on the left hand side of the figure. Therefore, wp_1 and wp_2 may share the link between N_1 and N_3 for protection. When also a node failure (NF) is taken into account, e.g. a failure of node N_3, the three paths wp_1, wp_3, and wp_4 are affected. This is reflected in G_{sg} in Fig. 3 on the right hand side by the additional edge. Note, that when there is a failure of node N_3, neither wp_1 nor pp_1 are feasible. Therefore, wp_1 and wp_3 may share protection resources.

B. Allocation of spare capacity for a PSG

Each PSG is handled separately. The minimization of the needed spare capacity for the PP of such a set is done by the following heuristic.

1. Sort the WP paths according to their hop-count.
2. Starting with the longest path, build a virtual network where the links used by the WP, are hidden. Add a constant to the weights of the links, which are not used until now for protection of this wavelength, which is larger then the sum of all weights in the network.
3. Assign the shortest path in the virtual network as the protection path for the investigated working path.
4. Continue the procedure with the next shorter path until an appropriate protection path has been found for all WP of this PSG and the needed spare capacity has been allocated.

In Fig. 4, an example configuration of the virtual network for the routing of the PSG with the black color in Fig. 3 of the network of Fig. 2 is depicted. The distances are noted in brackets, the dashed line shows a hidden edge. The PP for wp_1 and wp_3 are already assigned and the routing for the PP of wp_2 has to be calculated. The link between N_1 and N_3 may be reused.

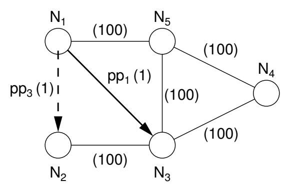

Fig. 4. Example configuration of a virtual network during PP routing for PSG.

For each WP, a PP can be allocated by this algorithm. These PP fulfill the imposed constrains of a correlated breakdown of several wavelength channels in case of a fiber break. The algorithm tries to maximize the reuse of protection resources.

The computational complexity of the algorithm is low and depends on the algorithm used to find the shortest path, but usually does not exceed $O(n \cdot m + n^2 \cdot \log n)$, where n and m denotes the number of nodes and edges, respectively [6]. Whenever a solution for the PP exists for the chosen WP, it will be found by the algorithm. Note, that when the WP are chosen in an improper way, it might be impossible to find e.g. a link and node disjoint PP.

The drawback of this procedure is that due to the separation of the search of a WP and its wavelength allocation from the planning of the shared protection capacity, only a suboptimal solution may be found. Nevertheless, similar techniques which have been used for the optimization of the routing and the wavelength allocation like simulated annealing [3] may also be applied to optimize the needed spare capacity. Here the first step for an iterative scheme consists of the routing and wavelength allocation for the WP, and in the second step the presented algorithm for the allocation of the spare capacity for one wavelength group may be utilized. The objective for the evaluation of the configuration should take into account the total needed resources.

For the assignment of the wavelength to WP and PSG, every algorithm or heuristic may be used as explained in the last section, but preferably the graph-coloring method as it has proved to perform well. For simplicity, it is assumed that a particular PSG is assigned only one wavelength. Here the generalization of a path as a set of edges (which must not be necessarily contiguous) is used.

Note that for the working path, a light-path with one wavelength for the whole path is assumed. In the network, some of the nodes might have the capability for wavelength conversion. Then, the formation of sets of paths which share their protection capacity among each other may not be performed on the basis of the (changing) wavelength of the paths. Instead the graph coloring method should be used to form virtual wavelengths for the assignment of the protection capacity.

V. Case Studies

The algorithm has been implemented using the `C++` class-library `LEDA` [6], which offers functions and standard algorithms to handle graphs and related data structures. To compare DP and SP for a given topology and traffic matrix, the program calculates the 10 shortest paths for each node pair. In case of DP, for each of these paths, the corresponding PP (if existing) is determined. Among these combinations of possible WP and PP for this node pair, the combination with the smallest total length $d(p_{wp}) + d(p_{pp})$ is chosen. Here, $d(p)$ is the length for the path p, and p_{wp} and p_{pp} denotes the WP and PP, respectively. All connection requests for the source and destination nodes described by the traffic matrix are assigned the same WP and PP. Wavelength assignment is done by the graph-coloring heuristic as described above.

In case of SP, the same WP as for DP is chosen. The PSG are formed and for the WP and PSG, the wavelength allocation is done as explained. All PP of one PSG are assigned the same wavelength (which is suboptimal, but simplifies the network management). The typical processing time on an Athlon 1000 PC for networks with up to 40 nodes and 300 edges amounts to only a few seconds. Though, with increasing number of connections which have to be established, the memory requirements is growing excessively. This is due to the fact, that the number of edges in the graphs G_{wc} and G_{sg} increases with the square of the number of connections. For example, in a random graph with 30 nodes, 156 edges and one connection among all node pairs (in total $29 \cdot 30 = 870$ connections), G_{wc} contains 1740 nodes and 103867 edges.

A. Rings

Rings are very attractive due to their simple routing and management. The solutions for DP and SP can simply be calculated. Therefore, rings has been used to test the algorithm for its correctness and performance.

The WP load L_{wp} is defined as the needed capacity in terms of the wavelengths on all fibers,

$$L_{wp} = \sum_{p \in P_{wp}} h(p), \tag{1}$$

to handle the WP. Here, $h(p)$ evaluates to the number of hops for the path p of the WP paths P_{wp}. The WP load L_{wp} depends on the chosen routing for the WP, but not on the algorithm used for the wavelength allocation. The same way, the total capacity L_{tot} is defined as the needed capacity to accommodate all WP and PP.

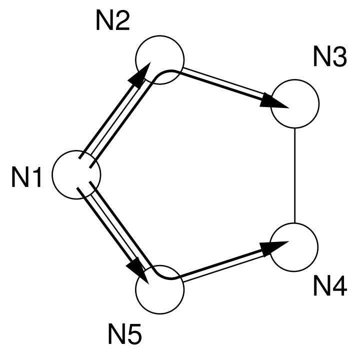

Fig. 5. Routing of WP for node N_1 in a ring with 5 nodes.

For rings with an odd number of network nodes, the routing for the shortest path policy is well-defined and depicted for a five node ring and node N_1 in Fig. 5. Assuming uniform traffic with one connection between every node pair and a fiber pair between the nodes, for every node $(n-1)/2$ connections advance in the clockwise and counter-clockwise direction. Therefore, in each fiber there are in total

$$\sum_{k=1}^{(n-1)/2} k = \frac{n^2-1}{8} \tag{2}$$

WP. In case of a failure, these have to be rerouted which means that the direction of traveling through the ring has to be changed. For DP, every bidirectional connection requires one wavelength channel on each link. Therefore in total $n \cdot (n-1)/2$ wavelengths are necessary and half of them are required as spare capacity for protection.

With SP, only the capacity needed to reestablish the disrupted paths has to be provided. Due to the high degree of symmetry, like in (2), $(n^2-1)/8$ additional wavelengths for protection are sufficient or in other terms (the additional factor of 2 accounts for the two directions in the ring), the protection capacity

$$L_{sp}(n) = \frac{n^3 - n}{4} \tag{3}$$

is needed.

For an even number of ring nodes, an ambiguity exists of how to route the paths with length $n/2$. When all are routed in the same direction (clockwise or counter-clockwise), (3) gives a lower bound.

n	3	4	5	6	7	8	9
$L_{wp}(n)$	6	16	30	54	84	128	180
$L_{sp}(n)$	6	15	30	52.5	84	126	180
$L_{wp} + L_{sp}$	12	31	60	106.5	168	254	360
DP: LF and LF + NF							
$L_{tot,DP}(n)$	18	48	100	180	294	448	648
# λ	3	6	10	15	21	28	36
SP: LF							
$L_{tot,SP_1}(n)$	12	36	60	124	173	280	369
# λ	2	5	6	11	13	19	22
SP: LF + NF							
$L_{tot,SP_2}(n)$	12	34	63	118	168	288	420
# λ	2	5	7	10	12	19	25

TABLE I
RESULTS FOR DIFFERENT RING SIZES n.

In Tab. I, the results for different ring sizes are given. Despite the fact, that there should be no difference between the two cases LF and LF together with NF, the performance and the solutions differ slightly. This is due to the way the PSG are formed and the heuristic to color the graph. The results are close to the theoretical lower bound. With increasing ring size the use of SP reveals to be more favorable.

B. The "Pan-European Network" of the COST 239 project

In the framework of the European project COST 239, several case studies for a Pan-European network have been performed [7]. In Fig. 6, the given fiber topology and in Tab. II the corresponding traffic matrix are depicted. As an example, a granularity of 2.5 Gbit/s and of 10 Gbit/s per wavelength has been assumed.

In Tab. III the results for a granularity of 2.5 Gbit/s per wavelength is given. In the case of DP and when only LF are investigated, more than twice the WP load of 545 is needed for the 348 connections, as expected. The total capacity is reduced from 1319 to 960 by using SP. Here, 29 PSG have been formed. For DP, 46 wavelengths are necessary in total, while for SP 37 are sufficient. The traffic load shows a strong variation among the links which is reflected by the range of 14 to 46 or 9 to 37 wavelengths on

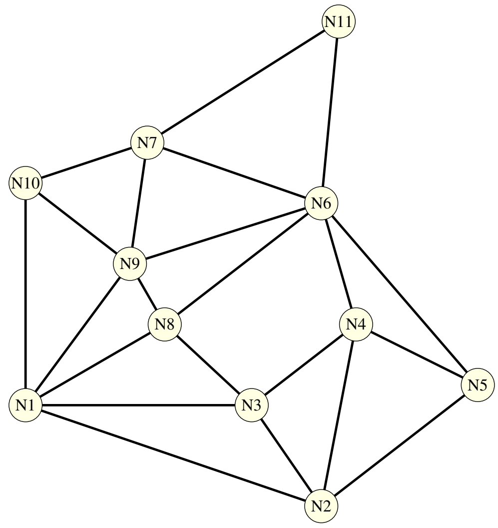

Fig. 6. Fiber topology according to the COST 239 case study for a Pan-European Network.

WP Load	545			
# Connections	348			
Failure	LF		LF + NF	
Protection	DP	SP	DP	SP
Capacity	1319	960	1323	1032
# PSG	-	29	-	47
# λ	46	37	49	40
min # λ	14	9	20	7
max # λ	46	37	49	40

TABLE III
RESULTS OF THE COST 239 CASE STUDY FOR A PAN-EUROPEAN NETWORK FOR CONNECTIONS OF 2.5 Gbit/s PER WAVELENGTH.

the links, respectively. This is due to the chosen routing and could easily be avoided by load balancing.

When in addition NF should be covered, a slightly increased capacity of 1323 is needed for DP. The changes for SP are higher: a capacity of 1032 is required. This is due to an increased number of mutual dependences among the paths and therefore 47 PSG have been formed. The performance is reduced in this case, which is also reflected in the amount of required wavelengths. Despite the small change in capacity for DP with 49 wavelengths, only three more wavelengths than for the case with LF are needed. A similar change is observed for SP.

For the granularity of 10 Gbit/s per wavelength, the corresponding results are shown in Tab. IV. The number of connections and the WP load have been reduced by about a factor of 1/2. This indicates that the channels are not efficiently used and there is spare capacity left.

When only LF are taken into consideration together with DP, 21 wavelengths in total are necessary to handle the traffic. With 10 wavelengths on the least loaded fiber, the

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11
N1	0	12.5	15	2.5	5	27.5	12.5	2.5	17.5	25	2.5
N2	12.5	0	15	2.5	7.5	22.5	5	2.5	5	7.5	2.5
N3	15	15	0	2.5	7.5	27.5	7.5	2.5	7.5	7.5	2.5
N4	2.5	2.5	2.5	0	2.5	5	2.5	2.5	2.5	2.5	2.5
N5	5	7.5	7.5	2.5	0	22.5	2.5	2.5	2.5	5	2.5
N6	27.5	22.5	27.5	5	22.5	0	20	5	15	20	7.5
N7	12.5	5	7.5	2.5	2.5	20	0	2.5	10	12.5	2.5
N8	2.5	2.5	2.5	2.5	2.5	5	2.5	0	2.5	2.5	2.5
N9	15	5	15	2.5	2.5	15	10	2.5	0	10	2.5
N10	25	7.5	7.5	2.5	5	20	12.5	2.5	10	0	2.5
N11	2.5	2.5	2.5	2.5	2.5	7.5	2.5	2.5	2.5	2.5	0

TABLE II

Traffic matrix of the COST 239 case study for a Pan-European Network in units of Gbit/s.

WP Load	246			
# Connections	149			
Failure	LF		LF + NF	
Protection	DP	SP	DP	SP
Capacity	598	442	602	493
# PSG	-	13	-	32
# λ	21	19	22	17
min # λ	10	4	8	4
max # λ	21	19	22	17

TABLE IV

Results for COST 239 case study for a Pan-European Network for connections of 10 Gbit/s per wavelength.

load is better balanced in the network. The savings with SP are similar to the 2.5 Gbit/s scenario and a reduction from 598 to 442 occurs for the required capacity. The reduction of the number of wavelengths from 21 to 19 is smaller. Due to the smaller number of paths, they have been grouped in only 13 PSG.

With the additional consideration of NF, the situation turns out to be similar. It is interesting, that for SP only 17 wavelengths are necessary. This is due to the different routing and indicates, that there is a potential for decreasing the number of required wavelengths by an optimized routing of the WP.

VI. Conclusions

The planning of shared protection for light-paths has been outlined for link failures as well as for link and node failures. The similarities between wavelength allocation and partitioning the working paths into sets which may share spare resources for protection using graph coloring, have been pointed out. Such a set is denoted a protection share group (PSG). A heuristic to route the protection paths for a PSG tries to minimize the total necessary capacity. The performance of both algorithms has been investigated using rings and the COST 239 case study for a Pan-European network. Significant savings compared to dedicated protection could be achieved especially for a high number of paths.

For routing, the shortest path policy results in unbalanced traffic pattern; more wavelengths are used than required to carry the traffic. By optimized routing, load balancing and a reduction of the used network resources like wavelengths could be achieved. In addition, numerical optimization techniques could be utilized for better grouping the PSG. Both aspects can easily be incorporated in the algorithms.

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