Protection, Routing, Modulation, Core, and Spectrum Allocation in SDM Elastic Optical Networks

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***Abstract*—Space division multiplexing is a promising solution, which has been proposed for elastic optical networks to deal with the anticipated exhaustion of the capacity of single core networks. This letter introduces the PERFECTA algorithm, a novel algorithm to provide failure-independent path protecting p-cycle for path protection in elastic optical networks using modulation and space division multiplexing.**

***Index Terms*—Survivability, multi-core fiber, elastic optical network with space division multiplexing, modulation.**

I. Introduction

SURVIVABILITY is of paramount importance in optical transport networks since these networks carry huge amounts of traffic. The larger the network capacity and consequently, the carried traffic, the greater is the need for efficient protection schemes to avoid massive loss of data. This vulnerability has motivated the development of various protection and restoration schemes for optical networks, including p-cycle which combines a rapid recovery in ring networks with the efficiency of topologically diversified grid networks. P-cycle employs pre-configured backup resources to permit the use of spare capacity in protecting working paths. Such pre-configured backup paths can shorten recovery time. P-cycle can protect both on-cycle and off-cycle spans as long as these spans have end-points on the p-cycle (straddling spans). One of the most explored types of p-cycle is the failure-independent path-protecting (FIPP) p-cycle which furnishes protection to end-to-end primary paths with end nodes on the p-cycle.

Another popular scheme for path protection in optical networks is the shared-backup path protection (SBPP) which defines pre-planned backup paths for disjoint primary paths. Besides the need of backup and primary path being disjoint, the backup path needs to have no common span with backup paths of any primary path that is not fully disjoint from its own primary path. Both SBPP and FIPP are failure independent which means that fault detection happens only at the end node without the need for fault location in real time no matter whether a node or a span has failed and where the failure has happened.

In this letter, we propose a routing, modulation level, spectrum assignment and core allocation problem (RMLCSA) [1]–[3] algorithm entitled the ProtEcting, Routing, modulation Format, corE and speCTrum Allocation algorithm (PERFECTA) for providing 100% protection against single failure for elastic optical networks with space division multiplexing (SDM-EONs). The PERFECTA algorithm chooses the shortest paths as primary paths and employs p-cycles as backup paths. It also uses a multigraph representation of the spectrum. The algorithm proposed considers not only protection, but also a variety of modulation formats. The PERFECTA algorithm differs from the algorithms in [4]–[6] by the employment of adaptative modulation and from the algorithms in [7] by the employment of p-cycle. The algorithms in [4]–[7] deal with the employment of SBPP, spectrum overlap, two simultaneous failures, and minimum interference routing, respectively.

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II. Related Work

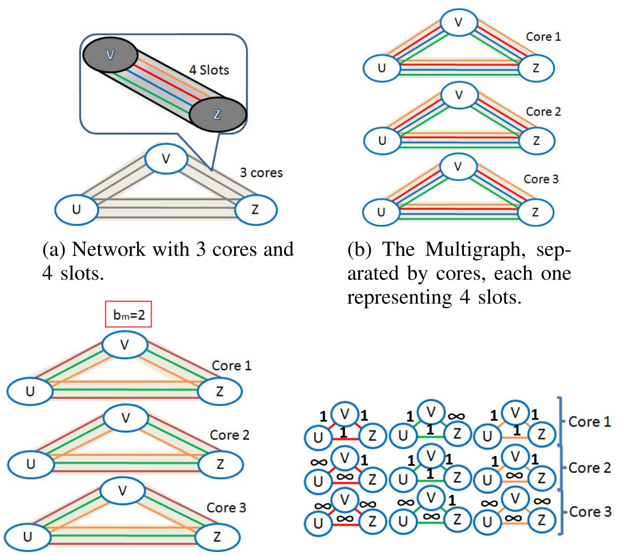
The work in [8] proposes a novel routing, modulation level and spectrum assignment (RMLSA) algorithm for elastic optical networks that considers the energy consumption of routes. The authors in [1] separated the routing, spectrum, and core and/or mode assignment problem into one for the routing and another for the spectrum, and core and/or mode assignment problems; a pre-computation method based on the K-shortest path is introduced as the routing solution. The work in [9] proposed the use of K-shortest paths to calculate routes in an RMLSA solution and the allocation of the spectrum using the lowest starting slot in a spectrum available. Modulation is chosen as a function of the length of the paths, so that less spectrum will be used and yet the received signal successfully decoded by the destination. In [3], an FIPP p-cycle was proposed for the protection of elastic SDM-EONs, although the modulation formats were not considered.

The BARTRMAN algorithm, designed for protection of SDM-EON, employs SBPP, adaptive modulation and a multigraph representation of the spectrum, also employed in the PERFECTA algorithm.

The implementation of FIPP p-cycles in elastic optical networks has been studied but only in [3] protection for SDM-EONs was proposed. To the best of our knowledge, no other work has considered modulation in p-cycle protected SDM EONs.

III. The PERFECTA Algorithm

The PERFECTA algorithm determines on the establishment of lightpaths in an FIPP p-cycle protected network. Such lightpaths are established if and only if the network can be protected by an FIPP p-cycle against a single failure. PERFECTA employs an RMLCSA algorithm which considers the allocation of the same spectrum into each fiber along the route of a lightpath (continuity constraint), as well as the necessity of slots being contiguously allocated in the spectrum (contiguity constraint).



(a) Network with 3 cores and 4 slots.

(b) The Multigraph, separated by cores, each one representing 4 slots.

(c) The Multigraph in that set edges are mapped in to one edge, contiguity constraint.

(d) Graphs generated.

Fig. 1. Transforming multigraph into graphs.

The selection of the modulation level by PERFECTA depends on the distance between the source and the destination, since the greater the number of bits per symbol, the stronger is the signal attenuation which can lead to incorrect decoding of the signal at the receiver. Modulation levels with a larger number of bits per symbol consume more power than those with a lower number of bits per symbol, but they are more efficient, since the ratio of power consumed per bit is higher [8]. In this letter, 64QAM, 32QAM, 16QAM, 8QAM, QPSK and BPSK modulation formats are employed for extensions of 125, 250, 500, 1000, 2000 and 4000 km, respectively with slot capacities of 75, 62.5, 50, 37.5, 25 and 12.5 Gb/s. The maximum acceptable crosstalk (XT) values for 64QAM, 32QAM, 16QAM, 8QAM, QPSK and BPSK modulation format are -32, -28, -24, -21, -18, -16 dB, respectfully.

PERFECTA models the spectrum availability in the network as a labeled multigraph (Fig. 1a). A label on an edge represents the availability of that slot. A slot is considered available if not used by any existing lightpath and the crosstalk on that slot is below a pre-defined threshold value. In Fig. 1b, the multigraph is divided into C multigraphs, where C is the number of cores. Each multigraph is then transformed into further multigraphs, each with $N-b_m+1$ edges (Fig. 1c), with b_m being the bandwidth demand in slots on the basis of the modulation format chosen [8]. Each of these multigraphs is then transformed into $N-b_m+1$ graphs. In other words, the original multigraph (Fig. 1c) is transformed into $C\times(N-b_m+1)$ graphs (Fig. 1d). Each edge in these graphs represents a combination of b_m slots. This representation assures spectrum contiguity in the solution. In these graphs (Fig. 1d), an ∞ label value means that at least one out of b_m slots is either allocated or has unacceptable crosstalk on it, whereas the value 1 means that all slots are available for allocation. When all edges of a graph have ∞ label value, the corresponding group of b_m slots is not available for allocation.

TABLE I
NOTATION

s: source node;
d: destination node;
b: bandwidth demand;
N: number of slots between two nodes;
C: number of cores;
V: set of nodes;
$e_{u,v,n}$: the n^{th} edges connecting u and v;
$E=\{e_{u,v,n}\}$: set of edges;
$G=(V,E,W)$: labeled multigraph composed of a set of nodes V, a set of edges E and a set of edge weight, W.
$m=1...M$: modulation formats;
b_m: bandwidth demand in slots in the basis of the modulation format chosen;
$r(s,d,b)$: request from the node s to the node d with bandwidth demand b;
$\delta(G,r(s,d,b_m))$: shortest path between s and d in G that satisfies the request for b_m slots ;
$w(e_{u,v,n})$: weight of the edge $e_{u,v,n}$;
$\widetilde{G}_{n,b_m}=(\widetilde{V},\widetilde{E},\widetilde{W})$: the n^{th} labeled graph such that $\widetilde{E}$ is the set of edges connecting $\{\widetilde{u},\widetilde{v}\}\in\widetilde{V}$ and $\widetilde{W}$ is the set of costs associated with $\widetilde{E}$. The edges in $\widetilde{E}$ correspond to the mapping of b_m edges in G, starting at the $n^{th}edge$;
$\sigma=|\{\widetilde{G}_{n,b_m}\}|=C\times(N-b_m+1)$: number of graphs extracted from the multigraph;
$\tau(G,C,b_m)=\{\widetilde{G}_{n,b_m}\}$: function which produces all σ graphs from G;
P_n: chain of $\widetilde{G}_{n,b_m}$ such that the source node s is the least ordered node and d is the greatest ordered node;
$W(P_n)$: weight of the path P_n, which is the sum of the weights of all the edges in the chain;
$W_{P_{s,d}}$ = weight of the shortest path between s and d;
B_n: chain of $\widetilde{G}_{n,b_m}$ such that the number of vertices is equal to the number of edges, and every vertex has degree 2;
$B_{u,v}$: set of all p-cycles containing the vertices u and v in G;
$\theta(\widetilde{G}_{n,b_m},P_n,r(s,d,b))$: shortest cycle between s and d in $\widetilde{G}_{n,b_m}$, which $P_{B_{s,d}}$ are link disjoint to P_n;
$\upsilon(P_n,B_{u,v},r(s,d,b))$: p-cycle in $B_{u,v}$ which $P_{B_{u,v}}$ are link disjoint to P_n and satisfies the request of bandwidth b;
$W(B_n)$: the weight of the p-cycle B_n, which is the sum of the weights of all the edges in the chain;
$W_{B_{s,d}}$ = weight of the p-cycle which protects the path between s and d;

The notation used in this letter is summarized in Table I.

Requests for the establishment of lightpaths arrive dynamically, each invoking the search for an existing FIPP p-cycle is sought to protect the potential lightpath. These FIPP p-cycles protect disjoint primary paths. If no FIPP p-cycle is available to protect the potential lightpath, another path is sought to create a new FIPP p-cycle for the request. If, however, no path can protect the lightpath, none will be established.

The PERFECTA algorithm is introduced in Algorithm 1. Line 1 transforms the multigraph into $C\times(N-b_m+1)$ graphs. Line 2 computes the shortest path for all graphs $\widetilde{G}_{n,b_m}$ and choses the least expensive one. If all obtained weights for shortest path are ∞, it means that there is no path for the demand b which observes the contiguity constraint. Line 3 selects the path among all shortest paths which has the lowest weight value. If the weight of all the shortest paths is ∞ (Line 4), there is no path in the network that satisfies the request for b_m slots under the contiguity constraint. If no path is available, the request is then blocked (Line 5). Otherwise, a p-cycle to protect this lightpath is sought (Line 7). When there is a p-cycle which protects both an active request and a new request, a lightpath is established (Line 8) with the weight of the corresponding edges in the multigraph G changed

Algorithm 1 PERFECTA

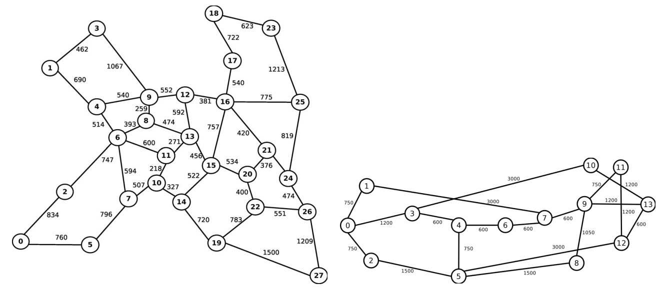
1: $\tau(G, C, b_m) \quad \forall m \in M$
2: $\quad (W(P_n), P_n) = \delta(\widetilde{G}_{n,b_m}, r(s,d,b)) \quad \forall n \in \sigma$
3: $\quad\quad W_{P_{s,d}} = W(P_n) | \; \forall i \; W(P_n) \leq W(P_i)$
4: **if** $W_{P_{s,d}} = \infty$ **then**
5: $\quad$ block $r(s,d,b)$
6: **else**
7: $\quad$ **if** $\exists v(P_n, B_{s,d}, r(s,d,b))$ **then**
8: $\quad\quad$ establish $r(s,d,b)$ as P_n and $B_{s,d}$
9: $\quad\quad w(e_{u,v,i}) = \infty \quad \forall \{u,v\} \in P_i$
10: $\quad$ **else**
11: $\quad\quad \tau(G, C, b_m) \quad \forall m \in M$
12: $\quad\quad\quad (W(B_n), B_n) = \theta\ (\widetilde{G}_{n,b_m}, P_n, r(s,d,b)) \quad \forall n$
13: $\quad\quad\quad W_{B_{s,d}} = W(B_n) | \; \forall i \; W(B_n) \leq W(B_i)$
14: $\quad\quad$ **if** $W_{B_{s,d}} = \infty$ **then**
15: $\quad\quad\quad$ block $r(s,d,b)$
16: $\quad\quad$ **else**
17: $\quad\quad\quad$ establish $r(s,d,b)$ as P_n and B_n
18: $\quad\quad\quad w(e_{u,v,i}) = \infty \quad \forall \{u,v\} \in P_i$
19: $\quad\quad\quad w(e_{u,v,i}) = \infty \quad \forall \{u,v\} \in B_i$
20: $\quad\quad$ **end if**
21: $\quad$ **end if**
22: **end if**

to ∞ (Line 9). If no such p-cycle exists, a new one is created to protect the lightpath to be established (Line 12). The creation of the p-cycle considers the shortest possible cycle connecting source and destination nodes, but if no such p-cycle can be created, then the request is blocked (Line 15). Otherwise, the primary path as well as the p-cycle (Line 17) are established. The weight of corresponding edges in the multigraph G is then changed to ∞ (Lines 18 and 19), meaning that the slots have been allocated to the newly established lightpath.

The complexity of the PERFECTA algorithm is analyzed next. The complexity of transforming the original multigraph into σ graphs is $M \times O(\|E\| + \|V\|)$, where M is the number of modulation levels that can be used. For the primary path, the Dijkstras algorithm is executed at most $M \times C \times (N - b)$ times. For creating p-cycles, the Suurballe's algorithm is executed at most $M \times C \times (N - b)$ times. Given that the complexity of both Dijkstras algorithm and Suurballe's algorithm are $O(\|E\| + \|V\| log \|V\|)$ and that C, N, M and b are constant values, the complexity of the PERFECTA algorithm is $O(\|E\| + \|V\| log \|V\|)$.

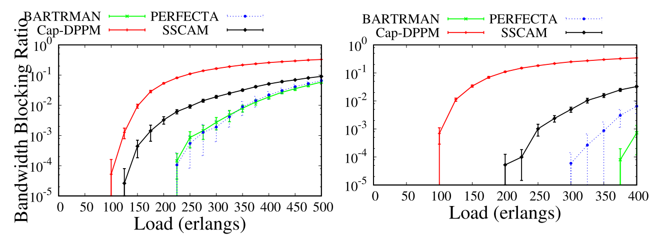
IV. Performance Evaluation

To assess the performance of PERFECTA in multi-core networks, simulation experiments were employed using 7 core fibers and the FlexGridSim [10] simulator. In each simulation, 100,000 requests were generated and simulations for all the algorithms used the same set of seeds. Confidence intervals of 95% confidence level were derived using the independent replication method. Seven types of request were considered; the bandwidth demand of a request was selected randomly from the values 25, 50, 125, 200, 500, 750 and 1000 Gbps. The Pan-European (Fig. 1a) and the national science foundation (NSF) (Fig. 2b) topologies were employed



(a) Pan-European Topology (b) NSF Topology

Fig. 2. Topologies.



(a) Pan-European Topology (b) NSF Topology

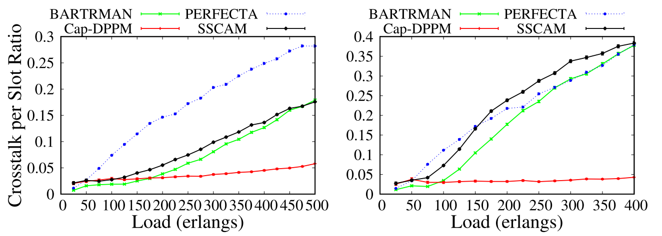
Fig. 3. Bandwidth blocking ratio.

in the evaluation of the effectiveness of PERFECTA. The NSF topology has 16 nodes and 25 links and the Pan-European topology has 28 nodes and 39 links. The traffic load was increased in units of 25 erlangs.

The spectrum was divided into 240 slots of 12,5 GHz each. In the figures, curves labeled Cap-DPPM show the results for networks using the crosstalk-aware provisioning strategy with dedicated path protection (Cap-DPP) algorithm proposed in [11] but with adaptive modulation. Curves labeled SSCAM (shared backup spectrum and core allocation and modulation) show the results for networks using the algorithm based on the methods proposed in [2] but employing protection and adaptive modulation. In SSCAM, the routing problem and the problem of spectrum, and core and mode assignment are solved separately. This approach employs pre-computed multiple primary and backup routes. The backup path uses a 1:N scheme for the SSCAM algorithm.

Fig. 3a shows the bandwidth blocking ratio (BBR) for the Pan-European topology. While Cap-DPPM and SSCAM start blocking requests for loads of 100 and 125 erlangs, respectively, PERFECTA and BARTRMAN start blocking only for loads of 225 erlangs. The BBR produced by PERFECTA and BARTRMAN are undistinguished for the role range of load. Under such loads, the difference between the BBR produced by the PERFECTA algorithm and those produced by the SSCAM and Cap-DPPM algorithm are one and two order of magnitude, respectively. The low BBR produced by BARTRMAN and PERFECTA evince the benefits of considering the multigraph representation of the spectrum to create primary and backup routes. The high BBR produced by Cap-DPPM is a consequence of not sharing backup paths. These results show that the PERFECTA algorithm produces acceptable blocking for SDM-EON despite the bandwidth reservation for preprovisioning of backup paths.

Fig. 3b shows the BBR as a function of the traffic load for the NSF topology. While Cap-DPPM, SSCAM



(a) Pan-European Topology (b) NSF Topology

Fig. 4. Crosstalk per slot ratio.

and PERFECTA start blocking request for loads of 100, 200 and 300 erlangs, respectively, the BARTRMAN algorithm starts blocking only for loads of 375 erlangs. For loads of 300 erlangs, the difference between the BBR produced by the PERFECTA algorithm and that given by the SSCAM and Cap-DPPM algorithms is almost three and four order of magnitude, respectively. For loads of 400 erlangs the difference between the BBR produced by the PERFECTA algorithm and that of the SSCAM algorithm is almost one order of magnitude. This happens due to the low node connectivity in the NSF topology which leads to the creation of bottlenecks. Although the difference in BBR between PERFECTA and BARTRMAN is nearly two orders of magnitude, such difference decreases rapidly to one order under 400 erlangs.

The use of several cores generates inter-core crosstalk. The crosstalk value associated with each spectrum slot is defined as the ratio of crosstalk index to the maximum value of the crosstalk index. The crosstalk ratio is defined as the average crosstalk value for all slots [12]. Fig. 4a shows the crosstalk per slot (CpS) as a function of the traffic load for the Pan-European topology. The use of PERFECTA leads to CpS values higher than those given by the others algorithms, a consequence of PERFECTA using a greater number of slots to create backup cycles. The crosstalk per slot as a function of the traffic load for the NSF topology is shown in Fig. 4b. The low connectivity of nodes in the NSF topology leads to the creation of bottlenecks, as well as greater CpS values than those produced for the Pan-European topology. The SSCAM algorithm produces the greatest CpS values, especially for heavy loads. The PERFECTA and the BARTRMAN algorithm produces similar CpS values close to those generated by SSCAM.

V. Conclusion

We have proposed an algorithm to support the establishment of lightpaths in elastic optical networks with SDM which are protected by FIPP p-cycles. The algorithm was evaluated for different topologies and traffic loads. The results obtained were compared to those generated by three other algorithms.

The PERFECTA and BARTRMAN algorithms employ adaptive modulation and a multigraph representation of the spectrum. An appropriate choice of modulation level avoids unnecessary slot allocation to cope with bandwidth demand. The multigraph representation of the spectrum allows decisions to be made considering a fine allocation granularity, thus avoiding fragmentation of the spectrum, leaving a larger number of contiguous slots available for future allocation. These two features make these two algorithms to have superior performance when compared to the SSCAM and Cap-DPPM algorithms.

Although the BARTRMAN algorithm may produce less blocking than the PERFECTA algorithm, the BARTRMAN algorithm presents the typical disadvantages of SBPP schemes. While the use of FIPP p-cycle involves pre-connected paths SBPP involves only pre-planned paths. In an event of failure, an SBPP scheme needs to dynamically establish the backup while for an FIPP scheme the backup is already established. As a consequence, the quality of transmission of the backup path chosen by an SBPP scheme cannot be guaranteed beforehand as in an FIPP scheme. Moreover, the restoration time of SBPP is much longer than that of an FIPP scheme [13]. Since the restoration time is one of the main metric for the evaluation of network protection, the somewhat greater blocking produced by PERFECTA algorithm when compared to that produced by the BARTRMAN algorithm may not be a definitive decision factor. Moreover, if only straddling p-cycles are chosen for creating FIPP, protection against two simultaneous failures is guaranteed.

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