A Novel Meta-Heuristic Approach for Optical Monitoring-Tree Design in WDM Networks

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Abstract—Thanks to recent advances in WDM technologies, an optical fiber is capable to carry up to 200 wavelengths operating at 40 Gbps each. In such high speed networks, service disruptions caused by network failures (e.g., fiber cut, amplifier dysfunction) may lead to high data losses. A network operator should be able to promptly locate such failures, in order to perform fast restoration. Hence, an efficient fault detection and localization mechanism is mandatory for reliable network design. In previous work, we have introduced the concept of monitoring-trees (m-trees) to achieve fast link failure detection and localization. We have proposed an integer linear programming (ILP) approach for the design of an m-tree solution that minimizes the number of required optical monitors, while achieving unambiguous failure detection and localization. In this paper, we propose a novel approach, based on the well known simulated annealing meta-heuristic, for the m-tree design in WDM networks. Simulations conducted in this study show the same results as the ILP approach at much lower computation time. Our proposal can thus be applied to large-sized and very large-sized networks.

I. INTRODUCTION

Optical transport networks continue to evolve towards higher data rates and increased wavelength density in WDM (Wavelength Division Multiplexing) technologies. In such networks, a single failure such as a fiber cut could result in the loss of a huge amount of information. Therefore, failure detection and localization is of paramount importance in provisioning reliable services with guaranteed quality of service (QoS). Furthermore, it is a challenging issue to operate dynamically reconfigurable transparent and translucent optical networks. In operated networks, the failure recovery protocols are implemented at different layers. A failure event at the optical layer then triggers alarms at the upper layers protocols [1]. An upper layer protocol often requires a much longer detection time than an optical/physical layer protocol. Hence, an intelligent and cost-effective monitoring mechanism dedicated to the network optical layer is mandatory.

In most existing approaches [2]–[12], the optical monitoring schemes consist in judiciously deploying optical monitors, responsible for generating alarms upon a link failure. Monitoring information (i.e., alarms generated by the monitors) are then submitted to the network’s control plane so that any routing entity is able to localize the failure and perform a real-time traffic restoration. In the aforementioned approaches, the monitoring techniques use dedicated supervisory channels at the detriment of operational lightpaths. More precisely, supervisory channels cannot carry users’ traffic. Such monitoring techniques are referred to as “out-of-band monitoring” in opposite to “in-band monitoring” where monitors are supervising operational lightpaths. Furthermore, the main concern of these approaches is to minimize the monitoring cost while unambiguously localizing a single link failure. The monitoring cost generally includes the number of required optical monitors, the number of required laser diodes, and the number of required supervisory channels.

In previous work [12], we have introduced a novel technique for unambiguous failure detection and localization, referred to as monitoring-tree (m-tree). The m-tree approach takes advantage of the broadcasting capability within an optical node, to keep the number of required supervisory channels to a minimum (i.e., number of network links). Furthermore, the m-tree approach uses a single laser diode at the head of the tree and aims at minimizing the number of required monitors. Therefore, the m-tree design problem consists in determining the position of the laser diode, minimizing the number of required monitors, and mapping a tree structure that allows us to unambiguously detect and localize any single link failure. In [12], we have proposed an ILP formulation to solve the m-tree design problem. In order to enhance the scalability of our solution, we propose in this paper a novel algorithm based on the well known simulated annealing (SA) meta-heuristic.

The remainder of this paper is organized as follows. In Section II, we draw a state-of-the-art of related work. We recall the concept of m-trees in Section III before going through the details of our SA-based algorithm in Section IV. Numerical results and analysis are given in Section V. In Section VI, we conclude our paper and provide directions for future work.

II. RELATED WORK

In the literature, the problem of failure detection and localization has been extensively addressed and many related works have been reported. As stated previously, an optical/physical-layer monitoring mechanism is most suited to achieve fast link failure detection and localization. In this section, we will focus on recent researches dealing with optical but out-of-band monitoring schemes.

One of the most basic monitoring schemes is the well known link-based monitoring, referred to as m-links. In the conventional m-link approach, the positions of laser diodes and optical monitors are straightforward. Each fiber-link is
equipped with a laser diode and an optical monitor at each of its ends, respectively. Hence, a single supervisory channel is reserved on each bi-directional link in order to detect any failure occurring on both directions of that link. Consequently, the $m$-link approach is able to detect and locate without any ambiguity any link failure as well as multiple link failures in the network. The drawback of the $m$-link approach is the excessive number of required laser diodes/optical monitors though it consumes the theoretical minimum number of supervisory channels. More sophisticated approaches target a reduced number of laser diodes/optical monitors while achieving unambiguous failure localization. In the late 2000s, two paradigms for failure detection and localization have been proposed, namely monitoring cycles ($m$-cycles) and monitoring trails ($m$-trails).

The $m$-cycle paradigm [2]–[5] has been proposed with the objective to reduce the number of required laser diodes/optical monitors, and subsequently to reduce the network monitoring cost. An $m$-cycle is defined as a loop-back optical connection associated with a laser diode and an optical monitor, placed back to back at any node on the loop. An $m$-cycle consumes an optical supervisory channel on each link it traverses. Although it significantly reduces the number of required monitors compared to the $m$-link approach, the $m$-cycle approach is unable, in some cases, to locate link failure without ambiguity. In order to resolve the ambiguity, extra link-based monitors are must.

In order to cope with the ambiguity, the concept of monitoring trails ($m$-trails) [6]–[9] has been proposed. An $m$-trail works the same way as an $m$-cycle but breaks the structure of the cycle, i.e., the laser diode and the optical monitor are not necessarily collocated at the same node. Therefore, both $m$-links and $m$-cycles can be considered as special cases of $m$-trails. It is worth noting that the number of optical supervisory channels is inversely proportional to the number of required laser diodes/optical monitors. Hence, the $m$-trail approach aims at achieving a tradeoff between laser diodes/optical monitors cost and bandwidth cost.

Recently, the $m$-cycles and $m$-trails approaches have been extended to achieve fast SRLG failure detection and localization [10], [11]. Shared risk link groups (SRLGs) refer to sets of network links sharing a common resource (e.g., fiber). If one link fails, other links in the same group may simultaneously fail. $m$-cycles start and end at the same node (monitoring location) whereas $m$-trails may start and end at distinct nodes (monitoring locations). Once monitoring locations are chosen, $m$-cycles ($m$-trails) are constructed such that any SRLG failure results in the failure of a unique combination of $m$-cycles ($m$-trails).

One major limitation of the $m$-trails is inherent to the fact they consume optical channels at the detriment of operational lightpaths. Since wavelength are scarce in optical networks, we introduced in [12] a novel approach for fast link failure localization referred to as "monitoring-trees" ($m$-trees). The concept of $m$-trees makes use of the broadcasting capability within a network node. Broadcast implies that an optical signal passing through a node can be duplicated an forwarded over two or more outgoing fibers. In opposite to the $m$-cycles and the $m$-trails, the $m$-trees consume a single optical supervisory channel per link. Moreover, since the signal duplication is performed in the optical domain, the optical supervisory signal is carried by the same wavelength on all the network links. Hence, the network blocking ratio, due not only to the lack of network resources but also to the wavelength continuity constraint, is reduced. Numerical results, presented in [12], outline the cost benefit we can achieve using $m$-trees.

### III. $m$-TREES DESIGN

As mentioned previously, the concept of $m$-trees takes advantage of the broadcasting capability commonly available in current WDM networks. Indeed, currently deployed network nodes are based on wavelength selective switching (WSS) technology enabling broadcast-and-select architecture. A node that is connected to three neighboring nodes, has a physical degree of four and its internal architecture is depicted in Figure 1. The additional degree is used to add/drop local traffic without any constraint on the source/destination of the traffic (directionless add/drop). In such an architecture, an incoming optical signal arriving at the splitter (Sp) of one degree/direction of the node is broadcasted to the WSSs of all the other degrees/directions of the node. Thus, a WSS associated with one direction of the node receives all the optical signals from all other directions. By suitably configuring the WSS, we can control which wavelength is transmitted on the outgoing fiber. As a result, an optical signal arriving at a node can be duplicated and forwarded over two or more outgoing fibers in a truly non-blocking manner.

Compared to existing approaches, the $m$-tree approach uses a single laser diode in order to monitor all the network links. In addition, it uses a single optical supervisory channel per fiber-link which corresponds to the theoretical minimum number of supervisory channels required for an unambiguous failure localization.

#### A. Example and Taxonomy

Let us consider a small example where we detail the $m$-trees concept. Consider the 5-node and 7-link network depicted in Fig. 1. WSS-based network node with a physical degree of 4.
and the monitors that are alerted for each link failure. Summarizing the links that are supervised by each monitor while the egress link of a fiber refers to a fiber carrying the initial signal before being duplicated, the fiber carrying the initial signal before being duplicated, or duplicated and sent towards multiple node over two or more links. Thus, a network link may have zero, one or more egress links. It is also shown in [12] that the alarm code associated with the failure of a link is equal to the sum of the alarm codes associated with the failure of the egress links. Thus, it is mandatory to place an optical monitor at the end of each link that has zero or one egress link in order to be able to localize without ambiguity any link failure. Furthermore, if the supervisory signal along an ingress link is duplicated and sent towards two or more nodes along different egress links, a new alarm code is associated with the failure of the ingress link and no optical monitor needs to be placed at its any of its ends.

- It is also shown in [12] that the optimal m-tree with the lowest number of optical monitors is a binary tree that duplicates, as much as possible, the supervisory signal into exactly two copies whenever the supervisory signal passes through a node. Thus, the theoretical minimum number of optical monitors required to monitor a network composed of |E| links is equal to \( \frac{|E|+1}{2} \).

It should be noticed that the position of the laser diode and the position of an optical monitor placed at the end of a link with no egress links can be exchanged without impacting the number of monitors required for this m-tree solution. Thus, in our previous example, by swapping the position of the laser diode with the position of the monitor located at the end of ‘link g’, a new m-tree solution obtained:

\[
g^H = \left( d^M \oplus c = (b^M \oplus a = (e^M \oplus f^M)) \right)
\]

This new m-tree solution is equivalent to the previous solution given by Equation (1). The operation required to move between these equivalent solutions is referred to as “Rotate Operation”.

### IV. Simulated Annealing-based Approach

In [12], we have proposed an integer linear program (ILP) approach for the design of an m-tree solution that minimizes the number of required optical monitors. This mathematical formulation was submitted to some commercial solvers such as Cplex [13]. However, the time required to solve this design problem ranges from few hours to several days according to the size of the considered network. In this paper, we propose a Simulated Annealing (SA)-based approach to solve the same problem in considerably reduced computation time. The SA

In Figure 2, we represent the m-tree solution and a table summarizing the links that are supervised by each monitor and the monitors that are alerted for each link failure.

Finally, we introduce two link attributes, namely “ingress link” and “egress link”. The ingress link of a fiber refers to the fiber carrying the initial signal before being duplicated, while the egress link of a fiber refers to a fiber carrying a single copy of the duplicated signal. It is worth noting that these attributes are only relative. For instance in our previous example, the ‘link a’ is the ingress link of ‘link c’ while being the egress link of ‘link e’ as depicted in Figure 2.

### B. Main Observations

Each network link, except the head of the m-tree, has a single ingress link. However, as stated previously, the supervisory signal arriving at a node can be terminated at that node, forwarded towards another node over a single link, or duplicated and sent towards multiple node over two or more links. Thus, a network link may have zero, one or more egress links. It is also shown in [12] that the alarm code associated with the failure of a link is equal to the sum of the alarm code associated with the monitor located at its end, if such a monitor exists, and the alarm codes associated with the failure of its egress links. Thus, it is mandatory to place an optical monitor at the end of each link that has zero or one egress link in order to be able to localize without ambiguity any link failure. Furthermore, if the supervisory signal along an ingress link is duplicated and sent towards two or more nodes along different egress links, a new alarm code is associated with the failure of the ingress link and no optical monitor needs to be placed at its any of its ends.

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algorithm is a randomized local search algorithm that proved its ability to find high quality solutions in short computation time. The basic idea of SA is to improve a given initial solution iteratively by applying defined rearrangement operations.

A. Initial Solution

The initial solution \( S_0 \) of the SA algorithm consists first in choosing a node with the smallest physical degree. If several nodes exist, we choose one randomly. Then, we randomly choose one fiber-link from the links connected to the selected node. The selected node will host the laser diode, while the selected link will represent the head of the m-tree. The other end of the selected link is now connected to our m-tree structure. At this node, we choose to broadcast the optical supervisory channel over all the other degrees/directions that are not yet used by our m-tree structure. The neighboring nodes that can be reached by the newly added links, are marked as connected nodes. By repeating the previous procedure for each connected node, our m-tree structure will progressively cover all the network graph.

Algorithm 1 Initial Solution

1: \( S_0 \leftarrow \emptyset \)
2: \( \mathcal{N} \leftarrow \emptyset \) \( \triangleright \) list of connected nodes
3: Select a node with the smallest physical degree. Let \( v_1 \) be this node.
4: Select a random link connected to \( v_1 \). Let \( e' = \{v_1, v_2\} \) be this link.
5: \( S_0 \leftarrow S_0 \cup \{e'\} \) \( \triangleright \) Add link to the m-tree solution
6: \( \mathcal{N} \leftarrow \mathcal{N} \cup \{v_2\} \) \( \triangleright \) Add node to the list of connected nodes
7: while \( \mathcal{N} \neq \emptyset \) do
8: Select a node \( v_j \) from \( \mathcal{N} \). \( \mathcal{N} \leftarrow \mathcal{N} \setminus \{v_j\} \)
9: for each link \( e'' = \{v_j, v_{2j}\} \in \mathcal{E} \) connected to \( v_j \) and \( e'' \notin S_0 \) do
10: Add \( e'' \) as an egress link to \( S_0 \). \( S_0 \leftarrow S_0 \cup \{e''\} \)
11: Add \( v_{2j} \) to \( \mathcal{N} \). \( \mathcal{N} \leftarrow \mathcal{N} \cup \{v_{2j}\} \)
12: end for
13: end while
14: Compute the number of required monitors \( C_0 \)
15: return \((S_0, C_0)\)

Once the m-tree is constructed, we go through each link of the network and an optical node is placed at the end of each fiber-link that has less than two egress links. Let \( C_0 \) be the total number of monitors that need to be deployed for an unambiguous failure localization using our m-tree structure. \( C_0 \) represents the cost of our initial solution \( S_0 \). The complete details for generating our initial solution is given by Algorithm 1. For this algorithm, we assume that the network physical topology is represented by a set \( V = \{v_i, i = 1 \cdots N\} \) of \( N \) nodes and a set \( \mathcal{E} = \{e_l = \{v_{1i}, v_{2i}\} \in V \times V, l = 1 \cdots L\} \) of \( L \) bi-directional fiber-links interconnecting these nodes.

B. Neighboring Solution

At each iteration of the SA algorithm, a new solution \( S_n \) is generated based on the current solution \( S_0 \). This new solution is obtained by a series of “Split”, “Rotate”, and “Combine” operations.

- The Split operation consists first in selecting a random link \( e' \) from \( S_n \) other than the head of the tree. Then, the link \( e' \) and all its subsequent egress links are removed from \( S_n \) and compose a first subtree denoted by \( S_0 \). The remaining links connected to the head of the tree compose the second subtree denoted by \( S_n \). Let us go back to our previous m-tree solution given by Equation (1) and let us assume that ‘link c’ was selected as the point of splitting. The resulting subtrees \( S_0 \) and \( S_n \) of this splitting operation are given by Equations (3) and (4), respectively.

\[
S_0 : \quad c = (d^M \oplus g^M) \\
S_n : \quad e = (f^M \oplus a^M = (b^M))
\]

- As introduced previously, the Rotate operation consists in swapping the head of the tree/subtree (usually hosting the laser diode) and a leaf of the tree/subtree with no egress links (usually hosting a monitor). Such rotate operation can be applied to any of the previously constructed subtrees. For instance, by rotating the subtree \( S_{0} \) given by Equation (3), one possible solution is given by Equation (5).

\[
S_{n} : \quad g = (d^M \oplus e^M)
\]

- Finally, the Combine operation tries to reconnect the two subtrees. This Combine operation can be carried out in different ways. One possible solution is to select the head of the subtree \( S_n \) as the head of the global m-tree solution \( S_n \). For instance, combining \( S_{0} \) and \( S_n \) given by Equations (4) and (5), respectively will results in

\[
S_n : \quad e^H = (f^M = (g^M \oplus e^M)) \oplus a^M = (b^M)
\]

The other alternative solution is to select the head of the subtree \( S_{0} \) as the head of the global m-tree solution \( S_n \). For instance, combining \( S_{0} \) and \( S_n \) given by Equations (5) and (4), respectively will results in

\[
S_n : \quad g^H = (e^M \oplus d^M = e = (f^M \oplus a^M = (b^M)))
\]

It should be noted that the Combine operation is not always successful. When this operation succeeds, we compute the total number of monitors \( C_n \) required for an unambiguous failure localization using the solution \( S_n \). Otherwise, \( C_n \) is set to infinity. The global procedure for generating a new solution \( S_n \) is given by Algorithm 2.

C. Decision Policy

At each iteration of the SA algorithm, we have to decide whether we continue searching the solution space based on the current solution or based on the newly generated solution. We recall that our objective is to minimize the monitoring cost expressed as the number of required optical monitors for an unambiguous failure localization. In this aim, a new
solution requiring less monitors than the current solution is accepted automatically (Line 9 of Algorithm 3). In order to avoid local minima, new solutions with larger number of monitors than the current solution are accepted with a probability determined by a control parameter $T$. However, the probability that these more expensive solutions are chosen decreases as the algorithm progresses in time to simulate the cooling process associated with annealing. This probability is based on a negative exponential function and is inversely proportional to the difference between the number of monitors of the current solution and the number of monitors of the new solution (Line 20 of Algorithm 3). If the new solution and the current solution use the same number of monitors, we randomly choose to accept the new solution as the current solution or reject it (Line 17 of Algorithm 3). The best solution obtained by the SA algorithm during its run is stored. Let $\mathcal{G}_b$ be this best solution and $C_b$ its corresponding number of monitors.

D. Convergence Criteria

As stated previously, the theoretical minimum number of optical monitors required to monitor a network composed of $|E|$ links is equal to $C_{th} = \frac{\lceil |E|+1 \rceil}{2}$. Thus, our SA algorithm stops when the number of monitors required for the best solution $C_b$ of the SA algorithm reaches $C_{th}$. However, as the theoretical minimum number of monitors is not always reachable, the SA algorithm may stop after attempting $k$ iterations without any improvement on the number of required monitors. The detailed description of our SA algorithm is given by Algorithm 3.

V. NUMERICAL RESULTS

In a first approach, we compare the performance of the proposed SA-based meta-heuristic (assuming $T = 0.5$, $p = 0.9$, $\kappa = 25000$) compared to the exact ILP formulation already proposed in [12]. For this aim, we have considered the medium-scale Deutsche Telekom (DT) network composed of 14 nodes and 23 bi-directional links depicted in Figure 3(c) and the large-scale Geant2 network composed of 34 nodes and 54 bi-directional links. For the DT network, the theoretical minimum number of monitors required for an unambiguous detection and localization is equal to 12. The optimal $m$-tree solution is found by solving the ILP formulation and is composed of 13 monitors. The time required to solve this problem is roughly 3 hours using a single-processor Cplex solver. Our SA-based approach was able to find this optimal result in less than 1 second. Similarly, for the Geant2 network, the theoretical minimum number of monitors required for an unambiguous detection and localization is equal to 28. The optimal $m$-tree solution is found by solving the ILP formulation and is composed of 29 monitors. The time required to solve this problem is roughly 7 days using a single-processor Cplex solver. Our SA-based approach was able to find this optimal result in less than 1 second. These two results highlight the capacity of the proposed SA-based approach to find the optimal result for networks of different sizes in reasonable computation time.

In a second approach, we compare the monitoring cost...
of the m-links, the m-trails, and the m-trees approaches for different networks, namely the 10-node 22-link SmallNet network (cf. Figure 3.a), the 21-node 25-link ARPA network (cf. Figure 3.b), the 14-node 23-link DT network (cf. Figure 3.c), and the 34-node 54-link Geant2 network. Table I summarizes the network resources occupied by the three approaches. According to the current optical equipment market, the cost of a laser diode is equal to the cost of an optical monitor which is 2.5 times more expensive than the cost of an optical supervisory channel. We can conclude that m-trees can achieve a cost saving of around 57% and 22% compared to m-links and m-trails, respectively.

VI. CONCLUSION

We addressed in this paper the problem of link failure detection and localization in WDM networks. Introduced in our previous work, the concept of m-trees takes advantage of the broadcasting property of a transparent network node. In doing so, the number of optical supervisory channels is kept to a minimum. Indeed, the m-tree approach uses a single laser diode located at the head of the tree and aims at minimizing the number of required monitors. The problem of m-tree design has been first solved using an ILP formulation. In this paper, we proposed a novel algorithm for the m-tree design, based on the simulated annealing meta-heuristic. Applied to practical-sized networks, our SA-based algorithm is able to find the same m-tree solutions as the ILP at much lower computation time (e.g., less than 5s against 7 days for the Geant2 network). Compared to its counterparts, m-links and m-trails, the m-tree approach is able to save 57% and 22% of monitoring cost, respectively. Meanwhile, relying on a single laser diode for monitoring the whole network is risky. In future work, we intend to extend our approach to multiple sub-trees. A sub-tree does not necessarily cover all the links of the network and does not need to be disjoint from other sub-trees. In order to increase monitoring reliability, we can choose to monitor the most loaded links by multiple sub-trees. Multiple sub-trees can be also used in order to detect multiple failures that may simultaneously occur in the network.

REFERENCES
