Monitoring-Tree: an Innovative Technique for Failure Localization in WDM Translucent Networks

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Abstract—Because of the very high optical fiber’s capacity, prompt and unambiguous fiber cut detection is mandatory to guarantee carriers’ network survivability. In this matter, the monitoring-cycle and the monitoring-trail mechanisms have been proposed in the recent literature. In this paper, we propose the innovative concept of monitoring-tree that enables to reduce considerably the monitoring cost while keeping unambiguous single fiber cut detection and localization. We propose an ILP formulation aiming at mapping a monitoring-tree onto a mesh topology. Applied to real networks, we show that our approach outperforms its counterparts.

I. INTRODUCTION

Optical transport networks evolve towards higher data rates and increased wavelength density in wavelength division multiplexing (WDM) systems. Optical component failures such as fiber cuts can lead to a huge amount of data loss. In transparent and translucent optical networks, failure detection and localization is a challenging issue to operate dynamically reconfigurable network with high reliability. Since failure recovery protocols are implemented at different layers, a failure event at the optical layer triggers in general alarms at upper layer protocols [1]. An upper layer protocol often requires a much longer detection time than an optical/physical layer protocol. Therefore, an intelligent and cost-effective monitoring mechanism dedicated to the network optical layer is mandatory.

Most existing approaches [2]–[8] consist in 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 control plane of the optical network so that any routing entity is able to localize the failure and perform a real time traffic restoration. In the proposed approaches, dedicated supervisory channels are used for monitoring purposes at the detriment of operational lightpaths. In other terms, supervisory channels cannot carry users’ traffic. Such monitoring schemes are referred to as “out-of-band monitoring” as opposed to “in-band monitoring” where monitors are supervising operational lightpaths. The major concern of these approaches is to minimize the monitoring cost while achieving an unambiguous failure localization. The monitoring cost generally accounts for the number of required optical monitors, the number of required laser diodes as well as the number of required supervisory channels.

In conventional link-based monitoring, the position of the laser diodes/optical monitors is straightforward. Each fiber-link is equipped with a laser diode and an optical monitor at each of its ends. Thus, a single optical supervisory channel is reserved on each bi-directional link in order to detect any failure occurring on both directions of that link. Consequently, this approach is able to detect and locate without any ambiguity any single link failure as well as multiple link failures in the network. Although this approach consumes the theoretical minimum number of optical supervisory channels, it consumes an excessive number of laser diodes and optical monitors which makes it less attractive for large networks. More sophisticated approaches aim at reducing the number of monitors in the network while achieving unambiguous failure localization. In the late 2000’s, two paradigms for failure detection and localization have been proposed, namely monitoring cycles (m-cycles) and monitoring trails (m-trails).

The m-cycles [2]–[5] have been proposed with the objective to reduce the number of required laser diodes and optical monitors, and subsequently to reduce the network monitoring cost. An m-cycle is a loop-back optical connection using a supervisory optical channel on each link it traverses, with a laser diode and an optical monitor placed back to back at any node along the loop. However, the major drawback of m-cycles is their inability to distinguish in some cases between single link failures occurring on different links. In order to localize each link failure without any ambiguity, extra link-based monitors are required.

The m-trails [6]–[8] have been proposed as an alternative for the m-cycles with the objective to unambiguously localize without any ambiguity any single link failure while still reducing the number of required laser diodes and optical monitors. An m-trail works in the same way as an m-cycle, but the optical connection of the supervisory channels is not necessarily a loop. Thus, the laser diode and the optical monitor of an m-trail are not necessarily collocated at the same node. As a result, both link-based monitoring and m-cycles can be considered as special cases of m-trails. It should be noted that the lower the number of laser diodes and optical monitors deployed in the network, the higher the number of optical supervisory channels required for an unambiguous detection. Thus, the m-trail approach tries to find a tradeoff between the cost penalty due to the additional number of
optical supervisory channels and the cost benefit due to the reduction in the number of laser diodes and optical monitors.

In this work, we propose an innovative approach for single link failure detection and localization in translucent WDM networks. Our approach, referred to as \( m \)-tree, takes advantage of the broadcasting capability within an optical network node in order to minimize the monitoring cost while achieving an unambiguous failure localization. In this paper, the problem of \( m \)-tree design is formulated as an integer linear program (ILP). The remaining of this paper is organized as follows. Section II provides a description of the \( m \)-trees design and alarm codes’ construction. In Section III, we present an ILP formulation of the \( m \)-tree design optimization problem. It is worth noting that we distinguish between small and medium size networks on one hand, and large size network on the other hand. In Section IV, numerical results are presented and compared to \( m \)-cycles and \( m \)-trails performance. Finally, we conclude our paper in Section V with some directions for future work.

II. PROBLEM DESCRIPTION

A. \( M \)-trees Design

One of the limitations of the \( m \)-trails is inherent to the fact they consume optical channels in the C-band at the detriment of operational lightpaths. Since wavelength resources are scare in optical networks, we propose 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 transparent network node. We mean by broadcast that an optical signal passing through a node can be duplicated and forwarded over two or more outgoing fibers. This functionality is highly available in current WDM networks. Indeed, commonly used fabrics are based on wavelength selective switching (WSS) technology enabling broadcast-and-select architecture. Such switch fabrics can provide multicasting and broadcasting facilities for every input channel in a truly non-blocking manner. A supervisory signal is not subject to reach limitations since it is evenly amplified. It has to be noted that it is insensitive to transmission impairments since the only information required at the monitors is the presence/absence of optical power.

For simplicity, 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, the ‘\( \text{link } b \)’ is the ingress link of ‘\( \text{link } c \)’ while being the egress link of ‘\( \text{link } a \)’ as depicted in Figure 1. As opposed to the \( m \)-trails which may use multiple optical supervisory channels per link on different wavelengths, the \( m \)-trees use of a single optical channel per link. Moreover, as the signal duplication is performed in the optical domain, the optical supervisory signal is carried by the same wavelength on all the network links. This does not only reduce the blocking ratio of the network due to the lack of network resources, but also reduces the blocking ratio due to the wavelength continuity constraint.

In the \( m \)-tree approach, a single laser diode is usually sufficient to monitor all the network. This laser diode is placed at a node and is transmitting its uni-directional supervisory signal over a single link referred to as the “head of the tree”. Arriving at a node along an input link, the supervisory signal can be terminated at the node, forwarded over a single outgoing link, or duplicated and sent over two or more outgoing links. By definition, a supervisory signal terminated at a node should be monitored at that node. Moreover, one may choose to monitor the supervisory signal at different locations in the network in order to be able to distinguish between different single link failures. A link with a monitor deployed at its end is referred to as a “leaf of the tree”. To sum up, for a network composed of \(|E|\) links, the \( m \)-tree approach requires a single laser diode, \(|E|\) optical supervisory channels, and less than \(|E|\) optical monitors in order to localize without any ambiguity each link failure in the network. It should be noted that the number of supervisory channels required by the \( m \)-trees is equal to the number of supervisory channels required by link-based monitoring approach which corresponds to the theoretical minimum number of supervisory channels required for an unambiguous failure localization.

Let us consider a small example to provide a deeper insight into the \( m \)-trees concept. Consider the 5-node and 7-link network in Figure 2. A possible \( m \)-tree solution would consist in placing the laser diode at ‘\( \text{node } 4 \)’. The supervisory signal generated at ‘\( \text{node } 4 \)’ is transmitted along ‘\( \text{link } e \)’ towards ‘\( \text{node } 2 \)’. At ‘\( \text{node } 2 \)’, the supervisory signal is duplicated and sent towards ‘\( \text{node } 0 \)’ and ‘\( \text{node } 1 \)’ along ‘\( \text{link } f \)’ and ‘\( \text{link } a \)’, respectively. At ‘\( \text{node } 0 \)’, the supervisory signal along ‘\( \text{link } f \)’ is terminated by a monitor which can detect any failure that occurs on any of ‘\( \text{link } f \)’ and ‘\( \text{link } e \)’. The supervisory signal arriving at ‘\( \text{node } 1 \)’ is duplicated and sent towards ‘\( \text{node } 0 \)’ and ‘\( \text{node } 3 \)’ along ‘\( \text{link } b \)’ and ‘\( \text{link } c \)’, respectively. At ‘\( \text{node } 0 \)’, the supervisory signal along ‘\( \text{link } b \)’ is terminated by a monitor which can detect any failure that occurs on any of ‘\( \text{link } b \)’, ‘\( \text{link } a \)’, and ‘\( \text{link } e \)’. Finally,
the supervisory signal arriving at ‘node 3’ is duplicated and sent towards ‘node 0’ and ‘node 4’ where these signals are terminated by two monitors. The monitor supervising ‘link g’ at ‘node 0’ can detect any failure that occurs on any of ‘link g’, ‘link c’, ‘link a’, and ‘link e’, while the monitor supervising ‘link d’ at ‘node 4’ can detect any failure that occurs on any of ‘link d’, ‘link e’, ‘link a’, and ‘link e’. In this example, ‘link c’ corresponds to the head of the m-tree while ‘link b’, ‘link d’, ‘link f’, and ‘link g’ are the leaves of the m-tree. 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.

B. Alarm Codes

An alarm code is a vector composed of several bits, each bit representing the state of an optical monitor. For instance, each line of the table in Figure 2 corresponds to an alarm code. To localize each link failure without any ambiguity, every link in the network must have a unique alarm code. As the number of optical monitors is undetermined a priori, we assume that each bi-directional link is assigned an optical monitor which can be deployed at one of the two ends of the link. One of the objectives is then to decide which of these optical monitors should be activated and which are useless and can be removed while preventing any coincidence between two alarm codes. As a result, for a network composed of [E] links, the alarm code is a vector of [E] bits where the corresponding bit of a deactivated optical monitor is always set to ‘0’. Upon the detection of a failure, an active optical monitor will set its corresponding bit to ‘1’.

As an illustration, if the failure of ‘link a’ would alert two optical monitors i and j, these monitors will set their corresponding bits to ‘1’ in the alarm code. Thus, the alarm code associated with the failure of ‘link a’ is a vector wherein only the ith and the jth bits are set to ‘1’, all the remaining bits being set to ‘0’. This alarm code can be viewed as the sum of two alarm codes: in the first alarm code, only the ith bit is set to ‘1’ while only the jth bit of the second alarm code is set to ‘1’. In general, the alarm code associated with a link failure is the sum of all the alarm codes associated with the monitors that would be alerted by the failure of the link.

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. Let us consider the general case where the supervisory signal is broadcasted towards multiple nodes. All the other cases can be deduced from this one. For this purpose, we will consider the example plotted in Figure 3. The supervisory signal arriving at ‘node 1’ along ‘link f’ is duplicated and forwarded towards ‘node 2’, ‘node 3’, ‘node 4’, ‘node 5’, and ‘node 6’. All the optical monitors that are capable of detecting the failure of ‘link a’ are also capable of detecting the failure of ‘link f’. This is also true for ‘link b’, ‘link c’, ‘link d’, and ‘link e’. Moreover, if there is an optical monitor at ‘node 1’ supervising ‘link f’, this monitor is also capable of detecting the failure of ‘link f’. Consequently, the alarm code associated with the failure of ‘link f’ is equal to the sum of the alarm codes associated with the failure of ‘link a’, ‘link b’, ‘link c’, ‘link d’, and ‘link e’ and the alarm code associated with the monitor located at the end of ‘link f’.

In general, the alarm code associated with the failure of a link is equal to the sum of the alarm code associated with the monitor at the end of the link, if such a monitor exists, and the alarm codes associated with the failure of its egress links. In mathematical form, this can be written as:

\[ \text{Alarm}_{\text{ingress}} = \text{Alarm}_{\text{monitor}} + \sum \text{Alarm}_{\text{egress}} \]  

(1)

C. Minimum Number of Monitors

By definition, a supervisory signal terminated at a node should be monitored at that node. Moreover, according to the previous equation, when the supervisory signal along an ingress link is forwarded along a single egress link, the alarm codes of both ingress and egress links will be equal unless there is a monitor placed at the end of the ingress link. Thus, it is mandatory to place an optical monitor at the end of each link that has a single 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, the alarm code associated with the failure of the ingress link is equal to the sum of the alarm codes associated with the failure of its egress links. By adding two or more alarm codes, a new alarm code is constructed which is sufficient for an unambiguous failure localization. Consequently, the optical monitor at the end of an ingress link that has multiple egress links is not necessary and can be removed.

As it can be seen in the previous example, we removed an unnecessary optical monitor at the end of an ingress link by combining the information brought by two or more egress links. However, the gain obtained is inversely proportional to the number of egress links. As a result, the optimal solution consists in duplicating and forwarding the supervisory signal along only two egress links. Therefore, the optimal monitoring 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. It is shown in [9] that a binary tree composed of n branches (n odd) has \( \frac{n+1}{2} \) leaves. Thus, the minimum
number of optical monitors required to monitor a network composed of \(|E|\) links is equal to 
\[\left\lfloor \frac{|E|+1}{2} \right\rfloor.\]

III. MATHEMATICAL FORMULATION

The \(m\)-tree design problem consists in defining the position of the laser diode, minimizing the number of optical monitors, determining their positions, and building a tree structure that allows us to detect and localize any single link failure without any ambiguity. The problem can be formulated as an ILP which can be solved by means of linear solvers.

A. ILP Formulation for Small-Sized Network

1) Parameters:
- The network physical topology is represented by a set \(V = \{v_i, i = 1 \ldots N\}\) of \(N\) nodes and a set \(E = \{e_l = (v_i^l, v_j^l) \in V \times V, l = 1 \ldots L\}\) such that \(v_i^l < v_j^l\) of \(L\) bi-directional fiber-links interconnecting these nodes.
- Let \(F\) be the set of all uni-directional fiber-links in the network. If \(e_l = (v_i^l, v_j^l)\) is a link in \(E\), then \(e_l = (v_i^l, v_j^l)\) and \(e_l \in F\) are links in \(F\). There exist \(2 \times L\) uni-directional fiber-links in the network. In the sequel, we use the notation \(e_l \in F\) to denote the link in the opposite direction of \(e_l\).
- As stated previously, each bi-directional link \(e_l \in F\) is assigned an optical monitor \(m_l\) which can be deployed at either end of the link. Upon the failure of a link, an active monitor \(m_l\) alerted by the failure of that link will set to ‘1’ the \(l^\text{th}\) bit of the alarm code. Thus, we assign to each monitor \(m_l\) an alarm code \(C_l\) where all the bits are set to ‘0’ except the one corresponding to the number of the monitor. The alarm code \(C_l\) can also be converted into its equivalent decimal value representation \(c_l\). Let \(C\) be the set of all the alarm codes assigned to the monitors; \(C = \{C_l, i = 1 \ldots L\}\).
- Two parameters \(A\) and \(B\) are defined as follows:
\[A > 2|E|\quad \text{and} \quad B < 2^{-|E|}\] (2)

2) Variables:
- The binary variables \(s_i\) \((i = 1 \ldots 2 \times L)\) for selecting the head of the tree. \(s_i\) is set to 1 if link \(e_i \in F\) is selected as the head of the tree; \(s_i\) is set to 0 otherwise.
- The binary variables \(d_i\) \((i = 1 \ldots 2 \times L)\) for selecting the leaves of the tree. \(d_i\) is set to 1 if link \(e_i \in F\) is selected as a leaf of the tree; \(d_i\) is set to 0 otherwise.
- The binary variables \(g_i\) \((i = 1 \ldots 2 \times L)\) for selecting the links belonging to the tree. \(g_i\) is set to 1 if link \(e_i \in F\) belongs to the tree; \(g_i\) is set to 0 otherwise.
- The binary variables \(z_{l,k}\) \((l, k = 1 \ldots 2 \times L)\) representing the way the supervisory signal is transmitted through the network. \(z_{l,k}\) is set to 1 if link \(e_k \in F\) is an egress link of \(e_l \in E\); \(z_{l,k}\) is set to 0 otherwise.
- The non-negative integer variables \(\text{lin}_{i,j}\) \((i, j = 1 \ldots L)\) used for intermediate calculation.
- The positive integer variables \(A_i\) \((i = 1 \ldots L)\) corresponding to the decimal representation of the alarm code associated with the failure of link \(e_i\) \((e_i \in E)\).
- The binary variables \(f_{i,j}\) \((i, j = 1 \ldots L)\) comparing the alarm codes associated with \(e_i\) and \(e_j\) \((e_i, e_j \in E)\).

3) Constraints:
- In the \(m\)-tree approach, a single laser diode is usually sufficient to monitor all the network. Thus, a single link is considered as the head of the \(m\)-tree.
\[\sum_{i=1}^{2 \times L} s_i = 1\] (3)
- The head of the \(m\)-tree as well as the leafs belong to the tree structure. \(\forall i = 1, \ldots, 2 \times L\)
\[g_i \geq s_i \quad \text{and} \quad g_i \geq d_i\] (4)
- Only the head of the \(m\)-tree generates a supervisory signal. All the other links copy the supervisory signal from another link having a node in common. \(\forall e_l = (v_i^l, v_j^l) \in F\)
\[\sum_{e_k=(v_i^k, v_j^k) \in F} g_k \geq g_l - s_l\] (5)
- All the bi-directional links belong to the \(m\)-tree structure. However, if a link \(e_l \in F\) belongs to the \(m\)-tree \((g_l = 1)\), the link in the opposite direction \(e_l \in F\) cannot be used \((g_l = 0)\). This will impact the placement of the optical monitor on that link. \(\forall e_l = (v_i^l, v_j^l) \in E\)
\[g_l + g_l = 1\] (6)
- The links that do not belong to the \(m\)-tree structure do not carry any supervisory signal. \(\forall e_l, e_k \in F\)
\[z_{l,k} \leq g_l \quad \text{and} \quad z_{l,k} \leq g_k\] (7)
- The supervisory signal cannot be transmitted from one link \(e_l = (v_i^l, v_j^l) \in F\) to another link \(e_k = (v_i^k, v_j^k) \in F\) unless they have a node in common \((v_i^l = v_j^k)\). \(\forall e_l = (v_i^l, v_j^l), e_k = (v_i^k, v_j^k) \in F\) such that \(v_i^l \neq v_j^k\)
\[z_{l,k} = 0\] (8)
- The head of the tree generates itself the supervisory signal and does not copy it from another link. In other words, the head of the tree does not have any ingress link. \(\forall e_l, e_k \in F\)
\[z_{l,k} \leq 1 - s_k\] (9)
- Only the links that are reported as leaves can terminate the supervisory signal. In other words, a leaf of the tree may not have any egress link. \(\forall e_l \in F\)
\[\sum_{e_k \in F} z_{l,k} \geq g_l - d_l\] (10)
- An ingress link may have multiple egress links. However, an egress link has one and only one ingress link. \(\forall e_k \in F\)
\[\sum_{e_l \in F} z_{l,k} = g_k - s_k\] (11)
- The head of the tree generates itself the supervisory signal. All the other links copy it from each other. Thus, the number of times the supervisory signal is copied is equal to \(|E| - 1\).
\[\sum_{e_l \in F} \sum_{e_k \in F} z_{l,k} = |E| - 1\] (12)
According to Equation (1), the alarm code associated with the failure of a bi-directional link \( e_l \in E \) can be expressed as:

\[
A_l = (d_l + d_{tr}) \times C_{lq}^d + \sum_{e_k \in E} \frac{(z_{l,k} + z_{r,k} + z_{l,kr} + z_{r,kr}) \times A_k}{\text{lin}_{z_{l,k}}}
\]

\[
= (d_l + d_{tr}) \times C_{lq}^d + \sum_{e_k \in E} \text{lin}_{z_{l,k}} \tag{13}
\]

- In the previous equation, the term \( \text{lin}_{z_{l,k}} \) is not linear because it is the product of a binary variable by an integer variable. Noticing that this product can be also written as \( \text{lin}_{z_{l,k}} = \min ((z_{l,k} + z_{r,k} + z_{l,kr} + z_{r,kr}) \times A, A_k) \), we can rewrite it in linear form as follows: \( \forall e_l, e_k \in E \)

\[
\text{lin}_{z_{l,k}} \leq (z_{l,k} + z_{r,k} + z_{l,kr} + z_{r,kr}) \times A \tag{14a}
\]

\[
\text{lin}_{z_{l,k}} \leq A_k \tag{14b}
\]

\[
\text{lin}_{z_{l,k}} \geq (z_{l,k} + z_{r,k} + z_{l,kr} + z_{r,kr} - 1) \times A + A_k \tag{14c}
\]

- All the network links should be monitored. Thus, none of the alarm codes should be equal to zero. \( \forall e_l \in E \)

\[
A_l \geq 1 \tag{15}
\]

- Finally, every link in the network must have a unique alarm code for an unambiguous failure localization. \( \forall e_l = (v_l^1, v_l^2), e_k = (v_k^1, v_k^2) \in E \) such that \( v_l^1 \neq v_k^1 \) or \( v_l^2 \neq v_k^2 \), \( B - 2 \times f_{l,k} \leq B \times (A_l - A_k) \tag{16a} \)

\[
f_{l,k} + f_{k,l} = 1 \tag{16b}
\]

4) Optional Constraints: The following constraints are not mandatory but they were used to speed up the execution of the solver used to find the optimal \( m \)-tree structure.

- The minimum number of optical monitors is equal to \( \left\lceil \frac{|E| + 1}{2} \right\rceil \). Thus, the \( m \)-tree has at least \( \left\lceil \frac{|E| + 1}{2} \right\rceil \) leaves.

\[
\sum_{i=1}^{2 \times L} d_i \geq \left\lceil \frac{|E| + 1}{2} \right\rceil \tag{17}
\]

- It is mandatory to place an optical monitor at the end of each ingress link that has a single egress link in order to be able to localize without ambiguity any link failure. \( \forall e_l \in E \)

\[
1 - 0.5 \times \sum_{e_k \in E} (z_{l,k} + z_{r,k}) \leq d_l + d_{tr} \tag{18}
\]

5) Objective: The objective is to minimize the number of deployed optical monitors while still achieving an unambiguous failure localization

\[
\text{Minimize } \sum_{i=1}^{2 \times L} d_i \tag{19}
\]

B. ILP Formulation for Large-Sized Network

The previous formulation is general and works for small networks up to 25 links. However, as the number of links increases, the parameters \( A \) and \( B \) become very large and very small, respectively. This leads to numerical instabilities in the linear solver. In order to cope with this problem, we propose to apply the following changes:

1) Parameters:

- We still assign to each bi-directional link an optical monitor which can be deployed at either end of the link. A monitor \( m_i \) is assigned an alarm code \( C_i^d \) composed of \(|E|\) bits where all the bits are set to ’0’ except the one corresponding to the number of the monitor. The alarm code \( C_i^d \) can be decomposed into blocks of 20 bits each. After converting each block of 20 bits into its equivalent decimal value representation, the decimal alarm code \( C_i^d \) assigned to a monitor \( m_i \) is then represented as a tuple \( \{C_{i,1}^d, C_{i,2}^d, \ldots, C_{i,|E|/20}\} \) composed of \( Q = \lfloor |E|/20 \rfloor \) components. Let \( C \) be the set of all the alarm codes assigned to the monitors; \( C = \{C_i^d, i = 1 \cdots L\} \).

- The two parameters \( A \) and \( B \) (cf. Equation (2)) are now defined as follows:

\[
A > 2^{20} \quad \text{and} \quad B < 2^{-20} \tag{20}
\]

2) Variables: The variables \( \text{lin}_{z}, A_l, \) and \( f \) should be redefined as follows:

- The non-negative integer variables \( \text{lin}_{z_{i,j,q}} (i, j = 1, \ldots, L, q = 1, \ldots, Q) \) used for intermediate calculation.

- The positive integer variables \( A_{i,q} (i = 1, \ldots, L, q = 1, \ldots, Q) \) corresponding to the decimal representation of the \( q \)th block of 20 bits in the alarm code associated with the failure of link \( e_l (e_l \in E) \).

- The binary variables \( f_{i,j,q} (i, j = 1, \ldots, L, q = 1, \ldots, Q) \) comparing the alarm codes associated with \( e_i \) and \( e_j \) (\( e_i, e_j \in E \)).

3) Constraints:

- The alarm code (cf. Equation (13)) associated with the failure of a bi-directional link \( e_l \in E \) is now expressed as: \( \forall e_l \in E, q = 1, \ldots, Q \)

\[
A_{l,q} = (d_l + d_{tr}) \times C_{lq}^d + \sum_{e_k \in E} \frac{(z_{l,k} + z_{r,k} + z_{l,kr} + z_{r,kr}) \times A_k}{\text{lin}_{z_{l,k},q}}
\]

\[
= (d_l + d_{tr}) \times C_{lq}^d + \sum_{e_k \in E} \text{lin}_{z_{l,k},q} \tag{21}
\]

- The variable \( \text{lin}_{z_{l,k},q} \) written in linear form (cf. Equation (14)): \( \forall e_l, e_k \in E, q = 1, \ldots, Q \)

\[
\text{lin}_{z_{l,k},q} \leq (z_{l,k} + z_{r,k} + z_{l,kr} + z_{r,kr}) \times A \tag{22a}
\]

\[
\text{lin}_{z_{l,k},q} \leq A_k \tag{22b}
\]

\[
\text{lin}_{z_{l,k},q} \geq (z_{l,k} + z_{r,k} + z_{l,kr} + z_{r,kr} - 1) \times A + A_k \tag{22c}
\]

- All the network links should be monitored. Thus, none of the alarm codes should be equal to zero (cf. Equation (15)). \( \forall e_l \in E \)

\[
\sum_{q=1}^{Q} A_{l,q} \geq 1 \tag{23}
\]

- Finally, every link in the network must have a unique alarm code for an unambiguous failure localization (cf. Equation (16)). \( \forall e_l = (v_l^1, v_l^2), e_k = (v_k^1, v_k^2) \in E, q = 1, \ldots, Q \) such that \( v_l^1 \neq v_k^1 \) or \( v_l^2 \neq v_k^2 \), \( B - 2 \times f_{l,k,q} \leq B \times (A_{l,q} - A_k) \tag{24a} \)

\[
\sum_{q=1}^{Q} (f_{l,k,q} + f_{k,l,q}) \leq 2 \times Q - 1 \tag{24b}
\]
4) Objective: The objective is still the same: minimizing the number of deployed optical monitors while still achieving an unambiguous failure localization (cf. Equation (19)).

IV. NUMERICAL RESULTS

As a first example, we consider the Deutsche Telekom (DT) network composed of 14 nodes and 23 bi-directional links depicted in Figure 4.a. For such a topology, the monitoring tree approach consumes a single laser diode at node 10 and 23 optical supervisory channels. The theoretical minimum number of monitors required for an unambiguous detection and localization is equal to 12. The ILP formulation for small-sized networks was submitted to a single-processor Cplex solver. The solver was able to find an optimal solution (cf. Figure 4.b) with 13 monitors in around 3 hours. In this solution, we note that links 1 - 8 and 13 - 14 have a single egress link. Thus, they have an optical monitor at their end.

As a second example, we consider the Geant2 network composed of 34 nodes and 54 bi-directional links. For such a topology, the monitoring tree approach consumes a single laser diode and 54 optical supervisory channels. The theoretical minimum number of monitors required for an unambiguous detection and localization is equal to 28. The ILP formulation for large-sized networks was submitted to a single-processor Cplex solver. The solver was able to find an optimal solution with 29 monitors in around 7 days.

In the following, we compare for the Deutsche Telekom network the monitoring cost of the link-based, the $m$-trails, and the $m$-trees approaches. 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. Let $r$ be the ratio of the monitor’s cost to the optical supervisory channel cost. We can conclude that the $m$-tree approach enables a gain in terms of monitoring cost of around 22% compared to the $m$-trails. It is worth noting that the $m$-tree approach remains economically more beneficial than the $m$-trail approach for any ratio of $r$ smaller than 6.5.

V. CONCLUSION AND OUTLOOK

In this paper, we introduced an innovative approach for detecting and localizing without any ambiguity any single link failure in the network. Our proposal takes advantage of the broadcasting capability within a transparent network node to keep the number of supervisory channels to a minimum. This theoretical minimum is equal to the number of network links. Moreover, our approach does not neglect the hardware cost. Indeed, it uses a single laser diode at the head of the tree and aims at minimizing the number of required optical monitors. The $m$-tree design problem consists in defining the position of the laser diode, minimizing the number of optical monitors, determining their positions, and building a tree structure that allows us to detect and localize any single link failure without any ambiguity. We proposed an ILP formulation which has been applied to real networks such as Geant2.

Meanwhile, relying on a single laser diode for monitoring the whole network is risky. Thus, we propose to monitor the network with 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