GMPLS Network Reliability Enhancement by Using the Dominating Nodes Approach

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Abstract—The impact of the control plane architecture on reliability of the GMPLS network is studied. To improve this reliability, a method based on the graph-theoretical dominating set problem is proposed. Several algorithms to select dominating nodes are presented and evaluated for four different network topologies by using simulation methods. It is shown that the service recovery time can be shortened by using the presented approach.

I. INTRODUCTION

The evolution of the Internet requires communication technologies which satisfy growing demand for bandwidth and allow for sophisticated services. The fiber optic technology can support sufficient bandwidth. However, high bit-rate transmission requires implementing IP switching over optical cross-connects (OCXs). Moreover, optical networking technologies need to support traffic engineering techniques in order to allow for advanced services like Voice over IP, IPTV, and others. The Automatically Switched Optical Networks (ASON) and the Generalized Multiprotocol Label Switching (GMPLS) are the key technologies which satisfy the growing requirements. These technologies are developed separately: ASON in ITU-T and GMPLS in IETF. However, GMPLS can be considered as the implementation technology of the control plane for ASON. The communication infrastructure based on ASON and GMPLS combines benefits of the fiber optic technology, IP routing and traffic engineering known from MPLS.

It is characteristic for ASON that functional planes can be physically separated. The main aim of this approach is the separation of signaling and management traffic from large-scale user data transmission. Thus, with out-of-band signaling, the opto-electronic processing of large-scale user data can be avoided.

The separation of functional planes can result in using different topologies for the data and control planes. In this case, two nodes directly connected in the data plane may not be connected in the control plane or, similarly, two nodes directly connected in the control plane may be not neighbors in the data plane. This kind of GMPLS architecture is called asymmetrical. If, however, the topologies of both planes are the same, the architecture is called symmetrical.

In order to support high performance transmission of user data, the GMPLS should be characterized by a high reliability. In our work, the reliability of a GMPLS network is considered assuming out-of-band signaling and the asymmetrical architecture. Papers [2], [3] and [4] show some aspects of failure detection and notification, also for different types of architectures and applied mechanisms.

Some issues of optical networks reliability are also considered in [5], [6] and [7]. The impact of control plane reliability on connection sustainability and control plane efficiency has been shown in [8]. The analysis of GMPLS network availability based on the transport network topology can be found in [9]. There exist many concepts to improve reliability of the GMPLS network. One of them is enhanced routing or signaling mechanisms for a better performance of network protection [10], [11].

In this paper, it is shown that a higher network reliability can be achieved by using optimization of the control plane topology based on the dominating nodes approach.

II. OPTIMIZATION CRITERIA

In order to objectively compare the GMPLS reliability several parameters are used [5]. These parameters allow describing the quality of transmission and quality of service offered by telecommunication providers. The most important, useful and easy in interpretation are the following parameters:

- Mean Time To Failure (MTTF) – defined as the mean period of time when a device is working without failure;
- Mean Time Between Failures (MTBF) – defined as the mean period of time between failures;
- Mean Time To First Failure (MTFF);
- Mean Time To Recovery or Mean Time To Repair or Mean Time To Restoration (MTTR) – defined as the mean period of time needed to repair failure or recover service;
- probability of failure $p$;
- availability $A$ (or unavailability defined as $U = 1 - A$).

Dependences between these parameters can be described by the following equation:

$$A = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{MTBF} = \frac{MTBF}{MTBF - MTTR} = 1 - \frac{MTTR}{MTBF} \quad (1)$$
where $MTBF \gg MTTR$ in most cases. The availability of the overall transmission system is represented by the following formula:

$$A = \prod_{i=1}^{n} A_i$$  (2)

where $A_i$ is availability of $i$-th element of the transmission system and $n$ is the number of system elements. Table I depicts typical availability values of network components. As shown, the fiber link is a component with the lowest availability. Damage of fiber links can disrupt user data transmission and services. Traffic engineering methods like restoration and protection prevent reliability degradation and keep the quality of service at an appropriate level in the case of failure of any network component. Of course, the protection and restoration procedures should recover service as fast as possible. The MTTR parameter represents how fast service recovery is achieved. Therefore, this parameter is chosen as an optimization criterion.

<table>
<thead>
<tr>
<th>Network device</th>
<th>MTBF (h)</th>
<th>MTTR (h)</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web server</td>
<td>$10^4 - 10^6$</td>
<td>1</td>
<td>$&gt; 99.99%$</td>
</tr>
<tr>
<td>Network card</td>
<td>$10^4 - 10^6$</td>
<td>2</td>
<td>$99.98%$</td>
</tr>
<tr>
<td>IP router</td>
<td>$10^4 - 10^6$</td>
<td>4</td>
<td>$&gt; 99.996%$</td>
</tr>
<tr>
<td>SDH/SONET device</td>
<td>$10^4 - 10^6$</td>
<td>6</td>
<td>$99.994%$</td>
</tr>
<tr>
<td>OXC optical switch</td>
<td>$10^4 - 10^6$</td>
<td>$10^2$</td>
<td>$&gt; 99%$</td>
</tr>
<tr>
<td>1000 km fiber</td>
<td>$10^4 - 10^6$</td>
<td>$10^2$</td>
<td>$&gt; 99%$</td>
</tr>
</tbody>
</table>

In order to provide high reliability of the GMPLS control plane, both the architecture and signaling procedures of the control plane can be optimized. The work [2] confirms dependency of the quality of service on the architecture. In particular, additional links between nodes in the control plane can speed up notification about failure and, therefore, improve recovery or protection procedures. The key issues related to the GMPLS recovery mechanisms can be found in [12] and RSVP-TE (ReSerVation Protocol – Traffic Engineering) extensions are described in detail in [13], [14] and [15]. The improvement is achieved when the RSVP Notify message is used instead of the RSVP PathError message. The source of this improvement is different signaling paths for the Notify and PathError messages. The PathError message pathway must be symmetrical to the Label Switched Path (LSP) of the pathway of user data. The Notify message can choose the shortest path to the destination independently of the LSP. Moreover, PathError must be processed by the RSVP module on each Label Switched Router (LSR) in the hop by hop manner, while Notify is sent directly to the destination. As a result, information about the failure reach the destination with a lower delay and protection or recovery can start faster. This improvement is especially significant in the case of end-to-end protection [14]. The discussed mechanism is presented in Figure 1. Note that in this procedure the edge nodes exchange several Notify RSVP messages. The additional handshake is required in the case of protection with extra-traffic and for some kinds of devices which need to reconfigure in order to receive traffic from another direction, another wavelength, etc. $t_{zu}$ is the period of time between the moment of failure and the moment of lost service detected by the end user (egress node), and $t_{pu}$ is the period of time between the moment of switching to the backup LSP and the moment of service recovery.

### III. DOMINATING NODES

As shown in [2], additional links in the control plane are able to improve reliability parameters. Interconnection of all nodes, however, is not economically justified. Moreover, [2] suggests that links between some nodes are more important than links between other nodes, so the authors suggest to use some algorithms to assign nodes which should be directly connected.

The described problem is similar to the well-known problem from the graph theory, i.e., the Dominating Set (DS) problem which is defined as the problem of searching of a set of dominating nodes D such that each node is in D or is a neighbor of D. There are several variants of this problem applicable to wireless and optical networks [16] [17]. One of the most important variants is the $k$-DS problem defined as follows: each node belongs to dominating set D or is at distance $k$ or less from at least one member of D. Note that for $k = 1$ this problem is the same as the classical DS problem described above. In the next sections, several simple $k$-DS algorithms are presented and used to select dominating nodes for some topologies. Finally, efficiency of these algorithms will be compared by simulations.

#### A. $k$-DS algorithms

The Dominating Set problem is a classic NP-complete problem. One of techniques used to solve such a problem is a heuristic which allows to get good, but usually not optimal, solution. The simplest heuristic algorithm used in this paper, denoted as BA (Basic Algorithm) algorithm, operates as follows:

1) each node is denoted by unique identifier ID,
2) set D as an empty dominating nodes set,
3) for each node $n$ calculate number of nodes $N(n,k)$ that are in the distance $k$ or less than $k$ from node $n$; if there exist multiple nodes with the same max $N(n,k)$ select the node with the smallest $ID$,
4) find node $n$ with max $N(n,k)$ and add this node to D,
5) repeat step 3 until D will be $k$-DS.

The presented algorithm is very simple and, as shown in the next section, is not optimal. Next, a more complex algorithm, denoted as EA (Easy Greedy Algorithm), introduces the set of covered nodes $C$ defined as a set of nodes that are in D or are in the distance of $k$ or less than $k$ from D. Again, the simplest algorithm with C defined in such a way can be formulated as follows:

1) each node is denoted by unique identifier $ID$,
2) set D as an empty dominating nodes set and C as an empty covered nodes set,
3) for each node $n$ calculate number of nodes $N(n,k)$ that are in the distance $k$ or less than $k$ from node $n$,
4) find node $n$ with max $N(n,k)$ such that $n$ is not in D and not in C; if there exist multiple nodes with the same max $N(n,k)$ select the node with the smallest $ID$,
5) add node $n$ to D, all nodes in the distance of $k$ or less than $k$ from node $n$ add to C,
6) repeat steps 3-4 until D will be $k$-DS.

The next four algorithms are variants of the EA algorithm. The first one is such that only a node that is not in the D set and is not in the C set is treated as a neighbor. This algorithm is denoted as GA1 (Greedy Algorithm type 1) and may be formulated as follows:

1) each node is denoted by unique identifier $ID$,
2) set D as an empty dominating nodes set and C as an empty covered nodes set,
3) for each node $n$ calculate number of nodes $N(n,k)$ that are in the distance $k$ or less than $k$ from node $n$ and are neither D nor C set;
4) find node $n$ with max $N(n,k)$ such that $n$ is not in D and not in C; if there exist multiple nodes with the same max $N(n,k)$ select the node with the smallest $ID$,
5) add node $n$ to D, all nodes in the distance of $k$ or less than $k$ from node $n$ add to C,
6) repeat steps 3-4 until D will be $k$-DS.

The next algorithm, denoted as GA2 (GA type 2), is such a modification of the GA1 algorithm that a new dominating node, found in step 4, may be the member of the covered nodes set. The next two algorithms, denoted GA3 (GA type 3) and GA4 (GA type 4), are such a modification of GA1 and GA2 algorithms, respectively, that from among candidates to be a dominating node with the same number of neighbors, the node with the largest number of directly connected neighbors is selected rather than the node with the smallest $ID$. The GA4 algorithm may be, therefore, formulated as follows:

1) set D as an empty dominating nodes set and C as an empty covered nodes set,
2) for each node $n$ calculate number of nodes $N(n,k)$ that are in the distance $k$ or less than $k$ from node $n$ and are neither D nor C set;
3) find node $n$ with max $N(n,k)$; if there exist multiple nodes with the same max $N(n,k)$ select the node with the largest number of adjacent nodes,
4) add node $n$ to D, all nodes in the distance of $k$ or less than $k$ from node $n$ add to C,
5) repeat steps 3-4 until D will be $k$-DS.

The last algorithm, denoted as EH, was described by M. El Houmaidi in [19] where it was used to calculate placement of wavelength converters in all-optical networks.

B. Topologies and theirs dominating sets

The algorithms described in the previous section were used to calculate dominating set nodes for several commonly used topologies such as NSFNET [18], U.S. Long Haul [19], Nobel_UE [20], and Cost266 [20] (shown in Figure 2). The number of nodes and the number of links for each topology are shown in Table II. The $k$-DS for $k = 1, 2, 3$ were calculated by using all algorithms described in the previous section. Results of these calculations are shown in Table III.

<table>
<thead>
<tr>
<th>Topology</th>
<th>Nodes</th>
<th>Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSFNET</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td>Long Haul</td>
<td>28</td>
<td>45</td>
</tr>
<tr>
<td>Nobel_UE</td>
<td>28</td>
<td>41</td>
</tr>
<tr>
<td>Cost266</td>
<td>37</td>
<td>57</td>
</tr>
</tbody>
</table>

As mentioned above, the selected nodes might be directly connected to achieve better reliability parameters. In some cases, however, the number of selected nodes is too high or too low. For example, the dominating nodes set selected by 3-DS algorithms for the NSFNET topology includes only one node, while the 1-DS BA algorithm for the Cost266 topology selects 26 nodes. Note that the number of nodes depends also on the algorithm which is used to calculate these nodes. The...
TABLE III
DOMINATING SET NODES FOR k-DS ALGORITHMS

<table>
<thead>
<tr>
<th>Topology</th>
<th>Algorithm</th>
<th>Dominating nodes k = 1</th>
<th>Dominating nodes k = 2</th>
<th>Dominating nodes k = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSFNET</td>
<td>BA</td>
<td>1,2,3,4,5,10,11</td>
<td>3,5,11</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>EA</td>
<td>1,6,8,10,11</td>
<td>7,8,11</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>GA1</td>
<td>1,5,8,10,13</td>
<td>7,8,11</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>GA2</td>
<td>1,5,9,10</td>
<td>1,11</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>GA3</td>
<td>1,6,8,10,11</td>
<td>7,8,11</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>GA4</td>
<td>1,3,5,10,11</td>
<td>10,11</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>HE</td>
<td>1,4,5,9,10,11</td>
<td>10,11</td>
<td>11</td>
</tr>
<tr>
<td>Long Haul</td>
<td>BA</td>
<td>1,2,3,4,5,8,10,12,15,16,17,20,22,25</td>
<td>4,8,12,16,17,25</td>
<td>8,12,16</td>
</tr>
<tr>
<td></td>
<td>EA</td>
<td>1,4,7,10,12,15,20,22,24</td>
<td>4,14,16,23</td>
<td>1,12,14</td>
</tr>
<tr>
<td></td>
<td>GA1</td>
<td>1,5,7,10,12,19,22,23</td>
<td>4,14,16,23</td>
<td>2,12,18</td>
</tr>
<tr>
<td></td>
<td>GA2</td>
<td>1,5,6,10,12,19,22,23</td>
<td>4,14,16,23</td>
<td>2,10,12</td>
</tr>
<tr>
<td></td>
<td>GA3</td>
<td>1,5,7,10,12,19,22,24</td>
<td>4,14,16,23</td>
<td>2,12,18</td>
</tr>
<tr>
<td></td>
<td>GA4</td>
<td>1,5,8,10,12,19,22,25</td>
<td>4,15,16,22</td>
<td>4,12,16</td>
</tr>
<tr>
<td></td>
<td>HE</td>
<td>4,5,8,10,12,15,17,20,22,25,27</td>
<td>4,16,17,25</td>
<td>8,16</td>
</tr>
<tr>
<td>Nobel_UE</td>
<td>BA</td>
<td>1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,27</td>
<td>3,5,9,10,11,12,13,14,15,16,22</td>
<td>5,9,11,12,16,22</td>
</tr>
<tr>
<td></td>
<td>EA</td>
<td>2,4,6,9,12,14,17,18,19,25,27</td>
<td>1,6,14,16,18</td>
<td>3,16</td>
</tr>
<tr>
<td></td>
<td>GA1</td>
<td>1,6,9,12,14,18,19,23,25,29</td>
<td>1,6,14,16,18</td>
<td>3,16</td>
</tr>
<tr>
<td></td>
<td>GA2</td>
<td>1,6,9,14,15,16,23,24,25</td>
<td>1,10,14,16,18</td>
<td>3,16</td>
</tr>
<tr>
<td></td>
<td>GA3</td>
<td>1,6,9,12,14,18,19,23,25,28</td>
<td>1,6,14,16,18</td>
<td>3,16</td>
</tr>
<tr>
<td></td>
<td>GA4</td>
<td>1,6,9,10,14,16,20,21,23,24</td>
<td>4,10,14,16,18</td>
<td>14,16</td>
</tr>
<tr>
<td></td>
<td>HE</td>
<td>3,4,8,9,10,14,15,16,17,18,20,21,22,24,27</td>
<td>4,9,13,14,16,22</td>
<td>9,14,16</td>
</tr>
<tr>
<td>Cost266</td>
<td>BA</td>
<td>2,4,5,6,8,9,12,13,14,15,16,18,19,20,21,22,23,24,26,27,28,29,30,32,34</td>
<td>4,5,8,13,15,18,19,20,25,26,29</td>
<td>8,13,18,20,24,25,29</td>
</tr>
<tr>
<td></td>
<td>EA</td>
<td>2,4,6,12,13,15,22,23,26,28,31,33,35,37</td>
<td>2,13,18,29,31,37</td>
<td>2,20,27,31</td>
</tr>
<tr>
<td></td>
<td>GA1</td>
<td>2,4,7,12,13,17,22,26,27,31,33,34</td>
<td>2,13,18,26,34</td>
<td>4,20,31</td>
</tr>
<tr>
<td></td>
<td>GA2</td>
<td>1,4,7,12,13,17,18,22,26,27,32,34</td>
<td>4,13,18,24,26</td>
<td>4,16,20</td>
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<td>GA3</td>
<td>2,4,6,12,13,15,22,23,26,28,31,33,35,37</td>
<td>2,13,18,26,34</td>
<td>4,20,31</td>
</tr>
<tr>
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<td>GA4</td>
<td>4,5,12,13,15,18,19,23,26,29,30,34</td>
<td>4,13,18,26,28</td>
<td>4,20,26</td>
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<tr>
<td></td>
<td>HE</td>
<td>4,5,9,13,14,15,16,18,19,20,26,27,28,29,30,36</td>
<td>4,13,18,20,26,29</td>
<td>13,18,29</td>
</tr>
</tbody>
</table>

C. Simulation tool and used network topology

The simulations are prepared with the use of the Network Simulator (NS-2) simulation environment [21], with an additional patch [22] and extensions prepared by the authors of [23]. These extensions allow to simulate GMPLS behavior with out-of-band signaling and the asymmetrical architecture. All implemented procedures and mechanisms have been tested and verified, and some results of simulations have been presented in [2], [24].

Two topologies, NSFNET and Nobel_UE, have been chosen to verify influence of the selected dominating nodes on the reliability. For both topologies several simulations were run:

- with the control plane topology symmetrical to the data plane topology, denoted as Ref;
- with the modified control plane topology, based on selected dominating nodes there all dominating nodes have been connected directly.

For the NSFNET topology, the dominating nodes set for $k = 1$ was chosen, and for Nobel_UE the dominating nodes set for $k = 2$. Moreover, the simulation with the topology based on the dominating nodes selected by the BA algorithm for $k = 2$ has been skipped because the number of selected nodes, and in consequence, the number of additional links were too high. The number of dominating nodes and the number of links are shown in Table IV. Note that some selected dominating nodes are directly connected in the symmetrical topology, and therefore, there is no need to connect them in the analyzed topologies.

For all simulations and for a given topology same traffic and failure patterns were assumed. The pattern contains:

- 10 randomly selected failures during 200 s of simulation (one failure per 20 seconds),
- 800 randomly selected connections with the dedicated 1:1 end-to-end backup (80 connections per failure).

The parameter that is measured is MTTR described in the previous section. The results of simulations for the NSFNET topology are shown in Figure 3, and for Nobel_UE in Figure 4.
In both cases, the 95% confidence intervals were calculated and presented.

The results confirm that the additional links in the control plane are able to reduce MTTR. This impact depends on the number of selected nodes and, first of all, on the number of added links. Note that in the case of nodes selected by the BA algorithm for the NSFNET topology the number of additional links is 14 while for the GA1 and EA algorithms the number of links is 10 and for the GA2 algorithm, only 4 additional links. In this context, the interesting result has been obtained for the EH algorithm where as many as 11 additional links is 14 while for the GA1 and EA algorithms the number of additional links based on finding the dominating nodes allows to reduce MTTR by only a few percent. A much better result was reached in the case of the Nobel_UP topology but, again, the number of additional links was bigger than that for the GA1 and EA algorithms.

IV. CONCLUSION AND FUTURE WORK

As expected, the simulations confirm the impact of the control plane topology on reliability of the GMPLS network. The additional links in the control plane are able to improve the MTTR parameter. The proposed method of determining additional links based on finding the dominating nodes allows to achieve satisfying results, but to obtain a deeper insight, the further research in this area is needed. The future work will be focused on developing of the presented method for more realistic network models with non-uniform traffic and bandwidth or delay of link represented by weighted edges in the graph. Cost-effectiveness of the proposed algorithms, especially in the context of the optical network devices availability values, is another issue to be considered in the future work.

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