Multi-layer Restoration in Hierarchical IP/MPLS over WSON Networks

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***Abstract*—Network operators are migrating to a multi-layer architecture with IP/MPLS equipment and optical nodes. Thanks to the advent of reconfigurable optical equipment and a multi-layer control plane, current 1+1 node protection at the IP layer in each location is not required anymore. This work studies the network availability in a national network with current 1+1 protection. To do so, an analytical expression is derived and validated via simulation in a typical operator scenario. With these results, this work concludes that it is possible to reduce the network equipment while maintaining the service availability currently offered to the clients.**

Keywords:Multi-layer traffic engineering; Multi-layer restoration; Protection mechanisms

I. INTRODUCTION

Current IP architectures are based on hierarchical structure, which is connected with high-speed point-to-point links via an optical network. With the advent of reconfigurable optical equipment, ROADMs give the possibility to establish direct light-paths between any two end points dynamically. Once the data plane is dynamic, the next step is to provide inter-layer flexibility. To do so, a multi-layer control plane is defined [1], which, on demand, can send the traffic either over the IP layer or the optical layer (via an existing light-path or creating a new one) [2]. There is an important on-going work on the definition of such multi-layer control plane and the interaction between the layers and other elements in the network, such as the Network Management System (NMS) or the Virtual Network Topology Manager (VNTM) [3].

The establishment of a path in an IP/MPLS network with a photonic mesh is not only a transport layer process. Once the path is set-up with the multi-layer control plane through the MPLS and the GMPLS equipment, the IP routers must be configured. Although there are efforts to standardize an interface to configure the IP routers [4], there is not a standard solution to configure the IP routers due to the information models of each vendor. Even if this interface were completely standard, a multi-layer network manager is required to coordinate such process [5].

Network survivability is an important study to deploy a solution in a real network. In current typical network operator's deployments, there are protection and restoration mechanisms for each layer. As there is no information exchange, between them it is not possible to coordinate the process. The current mechanism to avoid the activation of the survivability mechanisms at both layers is the use of different timers for each layer. With this timer-based approach, the optical layer triggers first its restoration mechanisms, while the IP/MPLS layer runs them only when the failure is not recovered at the optical layer.

The optical network protects the path based on the Class of Service (CoS) with fast protection and restoration mechanisms in a typical operator scenario. Regarding the IP layer, let us first describe its architecture. The standard configuration for an IP layer is hierarchical [6]. The first hierarchical level is composed by the access routers. Depending on the size of the operator, there are one or more levels with transit routers. The upper level of hierarchy is form by the interconnection routers. As the transit and interconnection routers have traffic of a lot of clients, there is typically a 1+1 protection per node. However, as there is a dynamic optical network and a multi-layer control plane, it is possible to think of new schemes such as using a router to protect a failure of N routers of a hierarchy. Such protection router can be in a different location with a pool of routers for protection purposes.

The research in multi-layer schemes is a topic of high interest for the research community. Authors in [7] propose multi-layer mechanisms in an ATM over SDH/WDM architecture. However, as the network technologies are changing, new studies are done based on current real networks. Authors in [8] study and define a new range of hierarchical restoration schemes in GMPLS-based recovery.

There is a lot of work done regarding algorithms in multi-layer networks. The scope of the research is wide: authors in [9] focus on defining new metrics to choose how to recover failures, authors in [10] present optimization algorithms to reduce the CAPEX in an IP/MPLS-Over-WSON network. The work in [11] presents routing mechanisms suitable for multi-layer restoration. The focus of this work is to compare the current 1+1 protection schemes in hierarchical network architectures with multi-layer restoration mechanism in order to measure the benefits of each approach.

This paper is organized as follows: Section II defines the survivability framework used in this work. Next, Section III describes the reference scenario for the study. Section IV derives an analytical expression of the problem. Such analytical expression is validated with simulation results in Section V. Finally, Section VI concludes this article and proposes future work.

II. SURVABILITY MECHANISMS

The network survivability mechanisms are directly related with the mean time between failures (MTBF) and mean time to repair (MTTR) parameters. In fact, ideally, a network with really high MTBF would not require survivability mechanisms because the network would never fail. As in real world, there are failures in the equipment, different protection and restoration mechanisms are proposed.

A. Protection

Protection mechanisms are based on the disjoint path idea where network planning plays an important role to define multiple paths where there are not resources shared. There are different protection schemes depending on the redundancy of resources, 1+1, 1:1, N:M.

B. Restoration

The restoration concept is based on computing the path after the failure, without any pre-computed backup path. Once a failure occurs, the nodes affected by the failure have to calculate a new path towards the destination (or ask for it).

This mechanism in comparison with protection has the benefit of a better resource usage due to the reduction of paths reserved for protection. The disadvantages are a longer recovery time and a less predictable network behavior making harder to plan the network.

C. Multi-layer Restoration

Multi-layer restoration idea is an extension of the restoration mechanism where multiple layer resources are involved in the restoration process. Since protection schemes and restoration schemes are defined in scenarios where all nodes, links and path are in the same layer, the network operators use combination of protection and restoration mechanisms in each layer separately.

Having more than one layer resources involved in the restoration process allow the network to calculate new and more complex paths to recover failures that with single layer protection and restoration schemes may be unable to be restored.

III. REFERENCE NETWORK

The network which is going to be studied is Telefónica's core network. This network presents two basic layers, IP/MPLS layer and a WSON mesh as transport layer.

A. IP/MPLS Layer

This network presents an IP/MPLS layer defined in a hierarchical way. This network has three levels defined which are the following:

- Access level
- Transit level
- Interconnection level

The access level is meant to be the first aggregation level in the core network where a big number of final users (typically 50k to 100k) are connected. This access level is meant to handle small cities regions with few customers and, in big cities, it handles districts.

The transit level has the goal of interconnect multiple access routers defining regions. Each region has a transit node (duplicated in case of using 1+1 protection scheme) which is connected to other regions by direct links between the transit routers allowing inter-region traffic. The transit level also aggregates traffic towards interconnection which is also known as "internet traffic".

The interconnection level aggregates all operator traffic which needs to be driven to other operators or other countries. Figure 1 presents an example of the Telefónica's hierarchical core network.

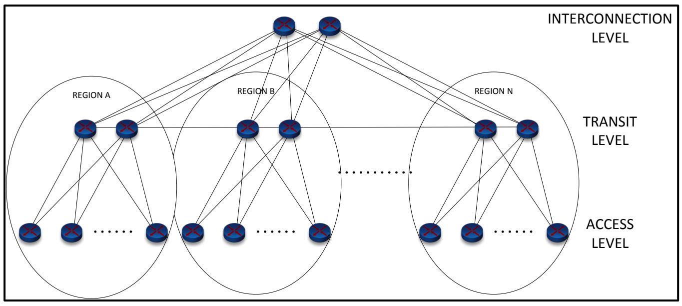

Figure 1. Hierarchical IP/MPLS Network

Current Telefónica's core network presents 1+1 protection in each network level all of them dimensioned to be able to drive at least the 100% of each region's traffic.

In this structure, the traffic is routed thanks to inter-domain routing protocols and other techniques to make the switching more efficient (such as MPLS): traffic coming from the edges of the IP network (interconnection or access nodes) crosses the IP network through the transit nodes to reach the other edges (interconnection or access nodes).

Each of the links between routers (IP links) is set up using the different transport technologies. Therefore, they can be implemented by the network operator by different means.

B. WSON Transport Network

In order to have a reconfigurable core network a GMPLS WSON mesh has been introduced. The WSON photonic mesh dynamic capabilities such as restoration and new link establishment via UNI interface allows the operator to perform multi-layer restoration operations.

The typical photonic mesh topology is basically done by connecting each router to one optical cross connect (OXC) and linking all OXCs that connected to a transit router. Figure 2depicts that network topology.

As can be seen in Figure 2, each region can reach, by transport layer links, other region's transit routers. As each transit router is dimensioned to handle the traffic of its region, other regions transit routers may restore the connectivity when a double failure occurs in one region.

According to this reference network, the multi-layer restoration use case needs to be studied in order to understand the benefits (if there are) of being able to connect to other regions and restore traffic in case of double failures that otherwise would meant network availability reduction.

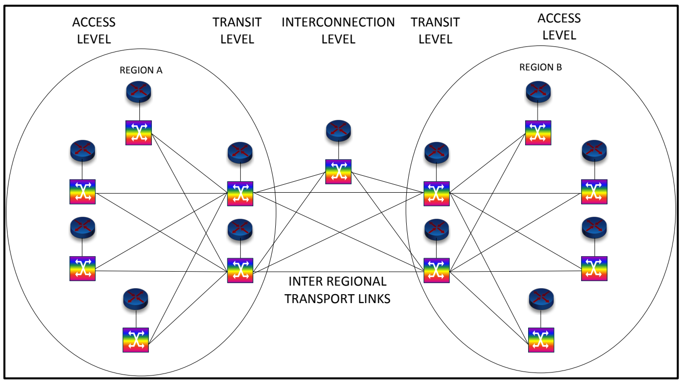

Figure 2. Hierarchical IP/MPLS over WSON network

IV. Analytical Study

The analytical study is based on the well-known Markov's chain model. This model is based on frequency of events reaching or leaving a state. In our case, the states are defined by the IP/MPLS nodes reachability status which can be:

- Failure: 1
- No Failure: 0

The transitions are defined by failure and fix events. These events are directly related to the MTTR and MTBF parameters. The MTTR means reparation or fixing a node in our model, due to this, it will be related to transitions from state 1 to state 0. In the other hand we have the MTBF that represents failures which applied to our model means a transition from state 0 to state 1.

$$0 \; to \; 1 \;\; \Rightarrow \lambda = \;\; 1 \, / \, MTBF \qquad (1)$$

$$1 \; to \; 0 \;\; \Rightarrow \mu = \;\; 1 \, / \, MTTR \qquad (2)$$

Parameter λ represents the frequency which failure events occur in the model and μ is the frequency of reparation events. Once the possibilities and the transitions are defined, the Markov's model is defined for the comparison between the multi-layer restoration and the 1+1 protection cases.

A. One Region

First, the problem is defined for one region where multi-layer restoration and 1+1 protection behave the same. As in one region there are two IP/MPLS transit nodes capable of driving the whole region traffic (1+1 protection 50% capacity dimensioning), the states can be defined as follows:

- 2 Active routers: No service affected
- 1 Active router: No service affected
- 0 Active routers Services affected

Assuming these three possible states, it is defined the following Markov's model in Figure 3. As the model shows, the transition between states 0 and 2 is forbidden, because a design assumption that makes impossible to happen 2 events at the same time.

The Markov's chain general expressions are the following:

$$\underline{\Pi}\underline{\underline{Q}} = \underline{0} \qquad (3)$$

$$\sum_i \Pi_i = \underline{1} \qquad (4)$$

Where $\underline{\Pi}$ is the states probability vector, that is, it has all the information about the probability of being in each state.

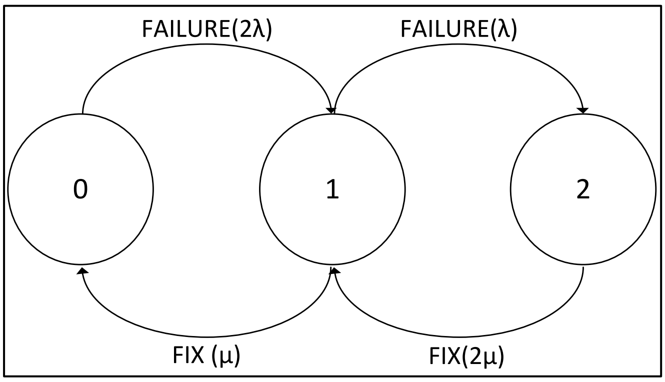

Figure 3. States Markov's model

Matrix $\underline{\underline{Q}}$ is the transition matrix that defines the events that relate all inter-state transitions. Applying the general expressions to our particular case:

$$\underline{\underline{Q}} = \begin{bmatrix} -2\lambda & 2\lambda & 0 \\ \mu & -(\mu+\lambda) & \lambda \\ 0 & 2\mu & -2\mu \end{bmatrix} \qquad (5)$$

$$\underline{\Pi} = [\Pi_0 \quad \Pi_1 \quad \Pi_2] \qquad (6)$$

Expanding Eq. (5), $\Pi_1$and Π_2 are derived as a function of Π_0. Then Π_0 can be obtained using Eq. (6).

$$2\lambda\Pi_0 = \mu\Pi_1 \;\Rightarrow\; \Pi_1 \;=\; (\lambda/\mu)\Pi_0 \qquad (7)$$

$$\lambda\Pi_1 = \mu\Pi_2 \;\Rightarrow\; \Pi_2 \;=\; (\lambda \, / \, \mu)^2\Pi_0 \qquad (8)$$

$$\Pi_0 = \; 1/(1 + 2(\lambda/\mu) + (\lambda/\mu)^2) \qquad (9)$$

Once each state probability is defined, the availability concept needs to be applied to the Markov's model already defined. In this case, as the routers are dimensioned in order of being capable of driving all traffic in the region, "unavailable" state is defined as the case where the two routers fails. In the model, this is the state two (Figure 3). Then, the probability of state two(Π_2) determines network's availability as follows:

$$A = 1 - \Pi_2 = 1 - (\lambda/\mu)^2\Pi_0 \qquad (10)$$

$$A = 1 - \frac{(\lambda/\mu)^2}{1 + 2(\lambda/\mu) + (\lambda/\mu)^2} \qquad (11)$$

Eq. (11) presents the network availability (A) as function of λ/μ. However, as λ/μ is not directly interpreted in terms of reparation or failure events, Eq. (12) presents the results as function of MTTR and MTBF.

$$A = 1 - \frac{(MTTR/MTBF)^2}{1 + 2\frac{MTTR}{MTBF} + \left(\frac{MTTR}{MTBF}\right)^2} \quad (12)$$

Figure 4 shows the network availability as function of MTTR/MTBF parameter in our one-region network case.

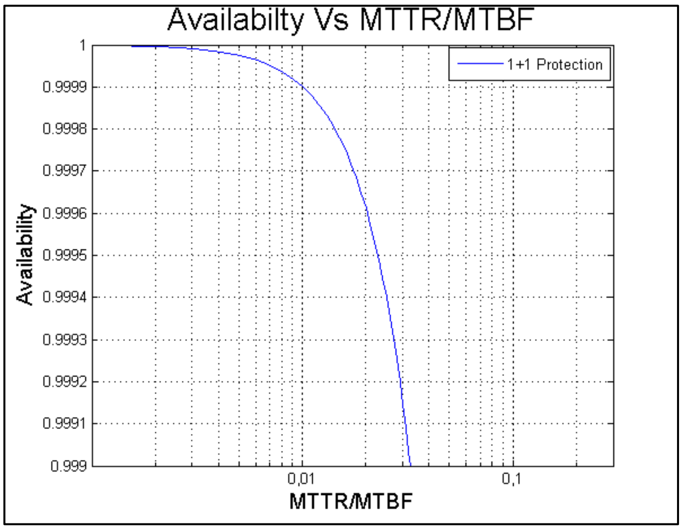

Figure 4. Availability vs. MTTR/MTBF in one region

The figure shows how the availability decreases when the MTTR/MTBF parameter grows. This behavior is expected because the greater is the delay to fix the nodes the lower is availability.

The next step is to present the Markov's model for the case with two regions where the multi-layer restoration mechanism presents differences with the 1+1 protection scheme.

B. Two Regions

The case with two regions and 1+1 protection presents the same results as the one region scenario. The availability is independent for each region due to there is no communication and resource sharing between them. The multi-layer restoration mechanism presents differences because the neighbor's transit routers are used to restore the traffic if both routers in the local region fail (double failure).

In case of double failure in a given region, the multi-layer restoration algorithm uses a foreign region to recover the traffic if it has enough resources and capacity to do drive the new traffic. Let us assume both regions have the same traffic capacity and the four transit routers also do. In that case, two of the four nodes are required at least to recover the whole traffic.

Figure 5 presents the Markov's model for the two regions in the multi-layer restoration case. This scenario presents as possible states 0 to 4 router failures.

The model presents five states where the same rules of the one region case apply here.

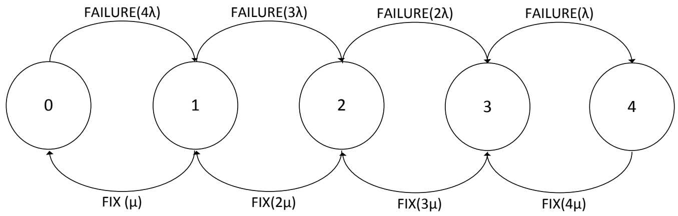

Figure 5. Two region multi-layer restoration Markov's model

Creating transition matrix $\underline{\underline{Q}}$ and using of Eq. (5) and (6), the following expression is achieved:

$$\underline{\underline{Q}} = \begin{bmatrix} -4\lambda & 4\lambda & 0 & 0 & 0 \\ \mu & -(\mu+3\lambda) & 3\lambda & 0 & 0 \\ 0 & 2\mu & -2(\mu+\lambda) & 2\lambda & 0 \\ 0 & 0 & 3\mu & -(3\mu+\lambda) & \lambda \\ 0 & 0 & 0 & 4\mu & -4\mu \end{bmatrix} \quad (13)$$

$$4\lambda\Pi_0 = \mu\Pi_1 \Rightarrow \Pi_1 = 4(\lambda/\mu)\Pi_0 \quad (14)$$

$$3\lambda\Pi_1 = 2\mu\Pi_2 \Rightarrow \Pi_2 = 6(\lambda/\mu)^2\Pi_0 \quad (15)$$

$$2\lambda\Pi_2 = 3\mu\Pi_3 \Rightarrow \Pi_3 = 6(\lambda/\mu)^3\Pi_0 \quad (16)$$

$$\Pi_0 + \Pi_1 + \Pi_2 + \Pi_3 + \Pi_4 = 1 \quad (17)$$

$$\Pi_0 = \frac{1}{1 + 4\frac{\lambda}{\mu} + 6\left(\frac{\lambda}{\mu}\right)^2 + 4\left(\frac{\lambda}{\mu}\right)^3 + \left(\frac{\lambda}{\mu}\right)^4} \quad (18)$$

Since the MTTR/MTBF target of this study is lower than 0.1, we can take into count only the grade two polynomial as representative of Π_0. According to this, we can start calculating the network availability. The states that can be defined as unavailable are $\Pi_3$and Π_4 so the availability expression is as follows:

$$A = 1 - \Pi_3 - \Pi_4 \quad (19)$$

$$k = MTTR/MTBF \quad (20)$$

$$A = 1 - \Pi_0(4k^3 + k^4) \quad (21)$$

$$A = 1 - \frac{4k^3 + k^4}{1 + 4k + 6k^2} \quad (22)$$

C. N Regions

Following the same procedure for the three and four regions cases, a general expression can be obtained to calculate the network availability for the n regions case.

$$\Pi_0(n) = \frac{1}{1 + 2nk + n(2n-1)k^2} \quad (23)$$

Where n is the number of regions. Then availability has the following expression:

$$A(n) = 1 - \Pi_0(n)\left(\sum_{i=n+1}^{2n} (k)^i \left[\frac{2n!}{(2n-i)!\,i!}\right]\right) \quad (24)$$

Making use of the availability expression, the following figure presents the comparison between the 1+1 protection mechanisms with the multi-layer restoration in hierarchical networks as described in the reference network chapter.

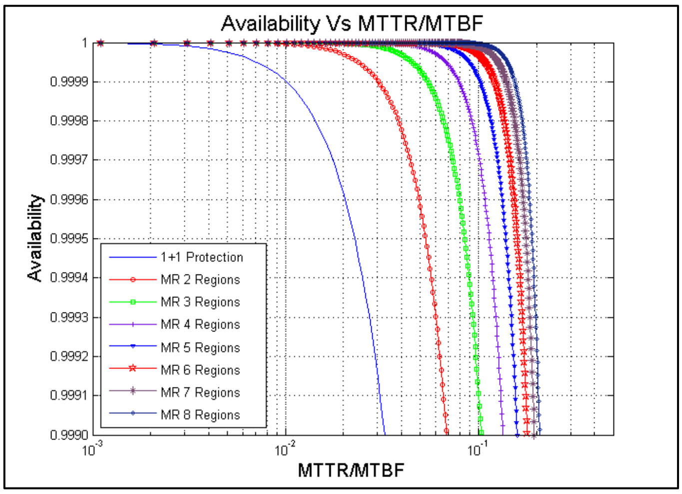

Figure 6. Availability Vs MTTR/MTBF comparison of 1+1 protection and 2 to 8 regions multi-layer restoration

V. Simulation Results

To validate the analytic study results, the reference network defined in Section III is simulated. The simulation environment is developed under Omnet++ v4.1, which is an event-oriented simulator.

As the study focuses in recovering IP/MPLS layer failures, the simulator generates randomly failures and fixes in the IP/MPLS transit nodes and cards. Both failures and reparations are described as a random process with an exponential distribution with MTTR and MTBF mean values.

Let us explain an example of how a failure and reparation process is simulated. When the simulation starts, all nodes and cards are working, then, failure events are generated following an exponential distribution with MTBF as mean parameter. When an event of failure occurs in one IP/MPLS node and the node state is marked as unavailable and the network starts to recover the connectivity if possible. At this certain moment, a random reparation event is generated following an exponential distribution with mean equals to MTTR parameter. Once the reparation event takes place, the IP/MPLS node is marked as available and is capable of driving traffic again.

A statically defined traffic matrix is used to load the network in a way all nodes are at 50% capacity when there is no failure in the network. This traffic matrix is based on demands, which can be defined as groomed traffic between access and interconnection routers. All regions have the same traffic capacity, the same number of access nodes and the same traffic distribution.

The availability parameter is calculated by measuring the period of time a demand is unavailable and comparing it to the whole simulation time.

$$A_{Demand} = 1 - \frac{\text{Demand unavailable time}}{\text{Simulation Time}} \qquad (25)$$

Then, calculate the whole network availability is reduced to calculate all demands availability mean.

The simulator network is composed by two topologies: (1) the physical topology, which represents the physical links between OXCs and between routers and OXCs, and (2) the logical topology, which represents the IP/MPLS topology.

The multi-layer restoration mechanism is implemented following the next steps:

1) A failure occurs.
2) The IP/MPLS nodes that have lost connectivity ask the multi-layer PCE for a path to another transit router with enough free capacity.
   1. There are free resources in the backup transit router in the region. The path includes the backup transit router.
   2. It is not possible to use the local region transit routers. A foreign region transit router is used to recover the traffic.
3) The IP/MPLS node using the answer received from the multi-layer PCE establishes the new path towards the new transit router.
4) When the failure is fixed, the traffic is re-routed to its original path and the resources used in the multi-layer restoration path are released.

Figure 7 shows a runtime simulation in the two-region case when a double failure is has occurred in one region and the traffic is being restored by means of the second region.

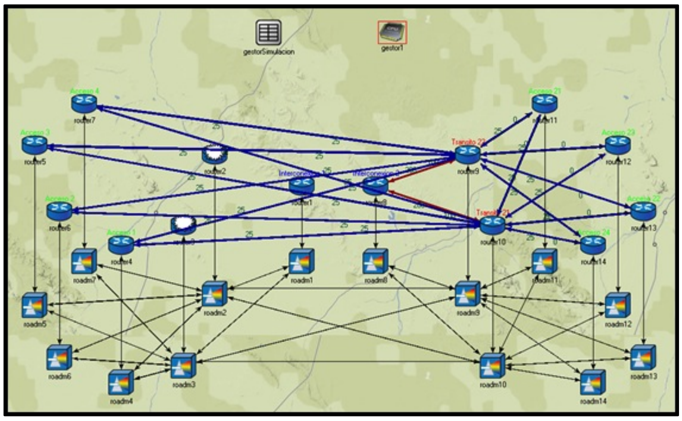

Figure 7. Double failure multi-layer restoration case in the simulator

The parameters used for the simulation are the following:

- MTBF: 1 to 5 Years
- MTTR: 0.5 to 180 days
- Simulation end time: 50 years

Figure 8 presents the results obtained in the simulation process. In this case, the failures have been only simulated in the nodes for comparing with the previously defined analytic failure model and as it can be seen, the results fit perfectly with the ones obtained in section IV. For better understanding of the graphic, the results of 4 to 8 regions are not shown.

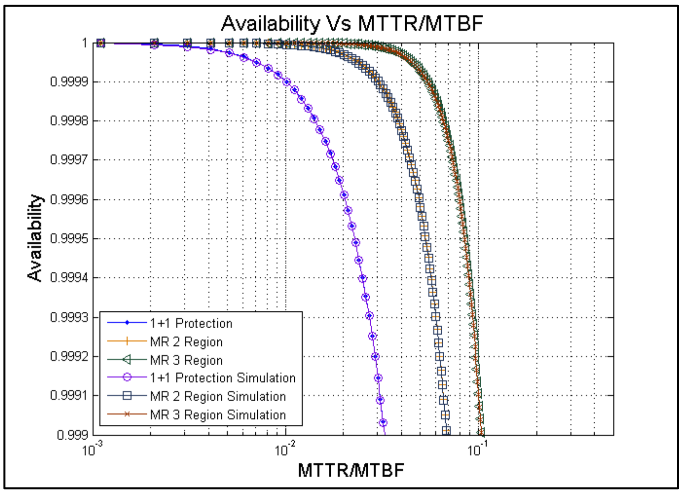

Figure 8. Simulation results compared with analytical results

The simulation has also been done including failures in IP/MPLS cards using the same MTBF value of the nodes. Is expected a lower availability due to the increase of failure points.

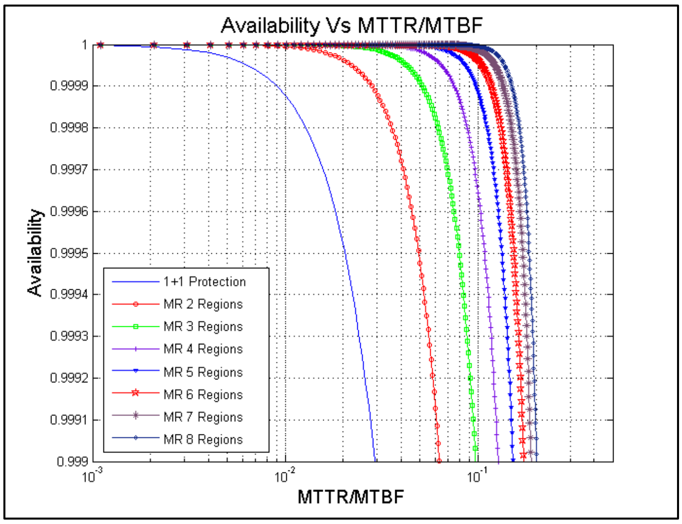

Figure 9. Simulation results

The simulation results are presented in Figure 9. The proportion between the availability increments by using the multi-layer restoration mechanisms is the same that in the only node failure case. The absolute results are in this are a little bit lower for all cases because of the failures in the IP/MPLS cards in the transit nodes.

As conclusion, multi-layer restoration presents higher availability results with the same resource usage of 1+1 protection mechanism. However, the 1+1 protection scheme can provide any availability goal if the MTTR is enough to cope with the failure frequency (MTBF). As conclusion of the simulation results it can be said the analytic study fits with the proposed multi-layer restoration scheme providing an interesting tool to quantify in future studies economic benefits of using multi-layer restoration mechanisms in hierarchical IP/MPLS core networks.

VI. Conclusions

This work compares the current 1+1 protection schemes in a realistic network scenario with the multi-layer restoration in order to compare the benefits of each approach. An analytic study and simulation results are done to test the performance of multi-layer restoration schemes.

In light of the results, we can see that the multi-layer restoration allows the network operator reducing the investment in IP routers for protection as the 1+1 mechanism is not required to provide current CoS agreements.

As future work, we will study the restoration mechanism with priority during the restoration process. This restoration mechanism with priority can protect with different requirements the traffic flows or regions depending on the failure. Moreover, we will work on a prototype to validate of the restoration mechanism with commercial equipment.

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