Incorporating Mutation Probability into Priority-Aware Protection in Optical Networks

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Abstract—**A persisting major challenge for optical network operators is to meet the various availability requirements of the different subscribed services through the deployment of effective protection strategies. Priority-aware shared protection is a promising scheme that has been proposed in the open literature as a potential approach to tackling this challenge. However, the priority-aware protection strategy is rigid in the sense that it privileges the high priority connections regardless of the low priority ones. Hence, this letter proposes to improve priority-aware protection by introducing the *mutation probability* parameter. This parameter expresses the likelihood that a high-priority connection be relegated temporarily to a lower priority level during recovery. In this way, the mutation-based protection strategy offers optical operators the possibility to increase the availability of their low-priority clients without violating the availability requirements of their high-priority ones. Performance of this novel protection strategy is analyzed in this letter by precisely calculating the connection availabilities resulting from its deployment.**

Index Terms—**Optical networks, survivability, performance evaluation.**

I. Introduction

FAILURES of optical network components (i.e. a fiber link, amplifier, transceiver, etc...) continue to weigh heavily on optical carrier operators due to the consequent huge data and revenue losses [1], [2]. Under such circumstances, the design of survivable optical networks became extremely important to operators who, through resource-efficient shared protection schemes, strategically try to restore a failed connection using backup resources shared upon a set of primary connections.

Classical shared protection schemes consider failed primary connections as equally important when contending for the use of the shared backup resources. However, from a quality of service perspective, these schemes are not optimal since they don't account for the different availability requirements of the failing primary optical connections during the course of recovery. This limitation led the authors in [3], [4] to define the so-called *priority-aware shared protection* scheme which differs from the classical scheme in that failed primary connections are recovered in an order consistent with their respective priority levels. In this context, the priority of a failed connection is determined by its availability requirement where a more stringent requirement translates into a higher urgency level during restoration. Nonetheless, continuously privileging higher priority connections severely penalizes low priority connections. As a result, low priority connections become unable to meet their own required availabilities and suffer an unfair severe availability decrease. Therefore, there is a need to modify the priority-aware scheme in such a way that alleviates the impact of high priority connections on lower priority connections. This should be done while bearing in mind that the availability requirements of high priority connections must not be violated. Inspired by these observations, this letter proposes a variant of the priority-aware protection scheme. The proposed variant associates with the high priority connections a parameter called mutation probability indicating the probability that a failed high priority connection be treated as a lower priority connection upon its recovery.

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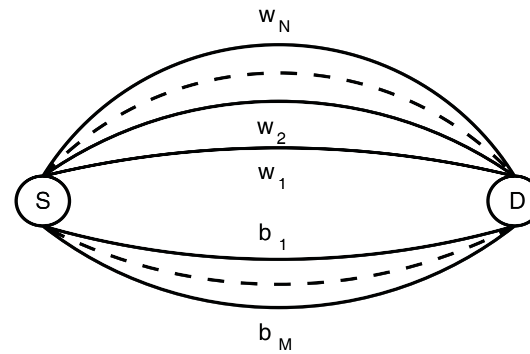

Fig. 1. N working paths sharing M backup paths.

II. Introduction of Mutation Probability to Priority-Aware Shared Protection

Consider N working paths (w_i, $i = 1, \ldots, N$) sharing M backup paths (b_i, $i = 1, \ldots, M$), *i.e.* an $M : N$ shared protection scheme as depicted in Fig. 1. For sake of simplicity, connections are considered to be arranged into 2 priority levels referred to as gold and silver respectively. Upon the failure of a primary connection t, if backup resources are available, then irrespective of its priority level, t is restored by any available backup path and repair process of t's primary path is started. As reparation completes, t is switched back to its working path.

If on the other hand upon t's failure, backup paths happen to be busy recovering connections with lower priority level than t then under the proposed protection strategy the mutation probability, P_{gs}, comes into play. As such, with a probability $(1 - P_{gs})$, t will be allowed to preserve its priority level and preempt one of the recovered lower priority connections that in turn becomes unavailable. Otherwise, with a probability P_{gs},

t will mutate from gold to silver and hence be deprived of its preemptive privileges thus becoming unavailable. So, in the proposed mutation-based shared protection scheme, a failed gold connection experiences a probabilistic transformation into silver, which helps to some extent reduce the greediness of gold. By fine-tuning P_{gs}, operators are expected to be capable of eliminating the unfair severe availability decrease experienced by silver connections while at the same time respecting the availability requirements of gold connections.

III. Unavailability Analysis: Mathematical Model

In this section, a mathematical model is provided to evaluate the average connection unavailability resulting from the deployment of the proposed protection scheme. Specifically, closed form expressions for the average unavailabilities of both gold and silver connections are derived in order to highlight the merit that the protection scheme under study has over the existing priority-aware shared protection scheme.

A. Basic Assumptions

The mathematical study is based on the following classical assumptions [3], [4]:

- A connection has only two states: it is either available or unavailable.
- Different network components fail independently leading to repair actions.
- Sufficient resources are available to repair simultaneously any number of failed connections, restoring them to be as good as new. This is known in the literature as *unlimited repair*.
- For any component the operation time and the repair time are independent stationary Markovian processes with known mean values: Mean Time To Failure ($MTTF$) and Mean Time To Repair ($MTTR$) respectively. $MTTF$ and $MTTR$ are computed based on the statistics presented in [5].

B. Model Definition and Resolution

Let us consider N primary paths sharing M backup paths (*i.e.*, an M:N shared protection scheme). The N primary paths are divided between N_1 gold connections and N_2 silver connections with $N_1 + N_2 = N$. To gain insight into the behavior of the system, a case of special interest is considered in which both primary and backup paths have identical failure and repair rates denoted respectively by $\lambda = \frac{1}{MTTF}$ and $\mu = \frac{1}{MTTR}$. Accordingly, both primary and backup paths behave identically and have the same availability of $p = \frac{\mu}{(\lambda+\mu)}$ as well as the same unavailability of $q = \frac{\lambda}{(\lambda+\mu)}$.

Unlike existing priority-aware shared protection schemes that give gold connections the upper hand under failure conditions, the protection strategy described in this letter proposes to treat a failed gold connection as a silver connection according to a given mutation probability denoted by P_{gs}. The value of P_{gs} is chosen in such a way so as to achieve the double objective of: (1) protecting silver connections against the greediness of the gold connections and (2) meeting the availability requirements of both gold and silver connections.

Let U_1 and U_2 denote respectively the unavailabilities of gold and silver connections. Finding U_1 and U_2 necessitates that the stochastic process $\{X(t), t \geq 0\}$ whose general state is denoted by the 4-tuple (n_1, n_1', n_2, m) be considered. In this regard, n_1 and n_2 are the number of failed gold and failed silver connections, n_1' is the number of failed gold that were subject to mutation and as a result treated as silver during the course of recovery, and m is the number of operational backup paths. Clearly, the stationary probability $Pr\{n_1, n_1', n_2, m\} = Pr\{n_1\} \times Pr\{n_1'|n_1\} \times Pr\{n_2\} \times Pr\{m\}$, where:

$$\begin{aligned} Pr\{n_1\} &= \tbinom{N_1}{n_1} \times q^{n_1} \times p^{N_1-n_1} \\ Pr\{n_1'|n_1\} &= \tbinom{n_1}{n_1'} \times P_{gs}^{n_1'} \times (1-P_{gs})^{n_1-n_1'} \\ Pr\{n_2\} &= \tbinom{N_2}{n_2} \times q^{n_2} \times p^{N_2-n_2} \\ Pr\{m\} &= \tbinom{M}{m} \times p^{m} \times q^{M-m} \end{aligned}$$

A silver connection t_2 becomes unavailable when both of the following conditions are verified:

- A: the primary path of t_2 is down.
- B: t_2 can not be restored by one of the M backup paths.

U_2, the unavailability of a silver connection, can thus be expressed as follows:

$$\begin{aligned} U_2 &= \sum_{(n_1,n_1',n_2,m)} Pr\{A, B, X = (n_1, n_1', n_2, m)\} \\ &= \sum_{n_1=0}^{N_1} \sum_{n_1'=0}^{n_1} \sum_{n_2=1}^{N_2} \sum_{m=0}^{M} Pr\{B|A, X\} \times Pr\{A|X\} \times Pr\{X\} \end{aligned}$$

Since all silver connections behave identically, it can be easily proven that:

$$Pr\{A|X = (n_1, n_1', n_2, m)\} = \frac{n_2}{N_2}$$

As mentioned earlier, n_1' gold connections out of the n_1 failed gold are relegated to a lower urgency level and hence act as silver connections during restoration. This means that $(n_1 - n_1')$ failed gold retain their urgency level and are given the highest priority with respect to the use of backup resources. The remaining $(n_2 + n_1')$ low priority connections can access the backup resources only after all $(n_1 - n_1')$ high priority connections have been recovered by the m operational backup paths. In light of this, $Pr\{B|A, X\}$ is given by:

$$Pr\{B|A,X\} = \begin{cases} 1, & m \leq (n_1 - n_1') \\ 1 - \frac{m-(n_1-n_1')}{n_2+n_1'}, & n_1 + n_2 > m > (n_1 - n_1') \\ 0, & otherwise \end{cases}$$

To sum up, U_2 can be written as follows:

$$\begin{aligned} U_2 = \frac{1}{N_2} \Bigg[& \sum_{n_1=0}^{N_1} \sum_{n_1'=0}^{n_1} \sum_{n_2=1}^{N_2} \sum_{m=0}^{(n_1-n_1')\wedge M} n_2 Pr\{n_1, n_1', n_2, m\} \\ & + \sum_{n_1=0}^{N_1} \sum_{n_1'=0}^{n_1} \sum_{n_2=1}^{N_2} \sum_{m=n_1-n_1'}^{n_1+n_2\wedge M} n_2 \frac{n_1+n_2-m}{n_2+n_1'} Pr\{n_1, n_1', n_2, m\} \Bigg] \end{aligned}$$

On the other hand, the computation of the unavailability of a gold connection U_1 should take into consideration the possible transformation of the failed gold into a silver. It is therefore necessary to distinguish between the case where the failed gold undergoes mutation and the case in which the failed gold maintains its class of service. In view of this, a failed gold connection t_1 is unavailable when either of the following 2 pairs of events occur:

- C: t_1 mutates from gold to silver, and D: the mutated t_1 is not restored.
- E: t_1 does not mutate to silver, and F: the non-mutated t_1 is not restored.

It follows that U_1 can be formulated as:

$$\begin{aligned} U_1 &= \sum_{n_1=1}^{N_1}\sum_{n_1'=0}^{n_1}\sum_{n_2=0}^{N_2}\sum_{m=0}^{M} Pr\{C,D,X\} + Pr\{E,F,X\} \\ &= \sum_{(n_1,n_1',n_2,m)} Pr\{X\}\times Pr\{C|X\}\times Pr\{D|C,X\} \\ &\quad + \sum_{(n_1,n_1',n_2,m)} Pr\{X\}\times Pr\{E|X\}\times Pr\{F|E,X\} \end{aligned}$$

It can be easily shown that: $Pr\{C|X\} = \frac{n_1'}{N_1}$ and that: $Pr\{E|X\} = \frac{n_1-n_1'}{N_1}$. Since D represents the case where the failed gold is converted into a silver, $Pr\{D|C,X\}$ is eventually equivalent to $Pr\{B|A,X\}$. As such, $Pr\{D|C,X\} = Pr\{B|A,X\}$. In the context of the considered protection strategy, the failed gold connections that don't go through mutation can immediately seize operational backup paths regardless of the number of failed silver connections there might be. So, the restorability of the $n_1 - n_1'$ non-mutated failed gold depends only on the number of operational backup paths (*i.e.*, m). As a result, $Pr\{F|E,X\}$, the probability that a non-mutated failed gold is not recovered, is given by:

$$Pr\{F|E,X\} = \begin{cases} 1 - \frac{m}{n_1-n_1'}, & m < (n_1 - n_1') \\ 0, & otherwise \end{cases}$$

In summary, U_1 is given by the following expression:

$$\begin{aligned} U_1 = \frac{1}{N_1}\Bigg[&\sum_{n_1=1}^{N_1}\sum_{n_1'=0}^{n_1}\sum_{n_2=0}^{N_2}\sum_{m=0}^{(n_1-n_1')\wedge M} n_1' Pr\{n_1,n_1',n_2,m\} \\ &+ \sum_{n_1=1}^{N_1}\sum_{n_1'=0}^{n_1}\sum_{n_2=0}^{N_2}\sum_{m=n_1-n_1'}^{n_1+n_2\wedge M} n_1' \frac{n_1+n_2-m}{n_2+n_1'} Pr\{n_1,n_1',n_2,m\} \\ &+ \sum_{n_1=1}^{N_1}\sum_{n_1'=0}^{n_1}\sum_{n_2=0}^{N_2}\sum_{m=0}^{(n_1-n_1')\wedge M} (n_1-n_1'-m) Pr\{n_1,n_1',n_2,m\} \Bigg] \end{aligned}$$

C. Numerical Results

This section evaluates the benefits of the proposed protection strategy by analyzing its impact on the availability of gold and silver connections. Various scenarios were tested, but due to space limitation only one of them is discussed. This scenario consists of $N_1 = 2$ gold, $N_2 = 8$ silver, and $M = 2$ backups. Following the guidelines presented in [5], the cut rate λ is set to a reference value of $1/750\,h^{-1}$ and a value of $1/12\,h^{-1}$ is used for the repair rate μ. Furthermore, it is assumed that a gold connection has an availability requirement of 99.999% while a silver connection requires an availability of 99.99%

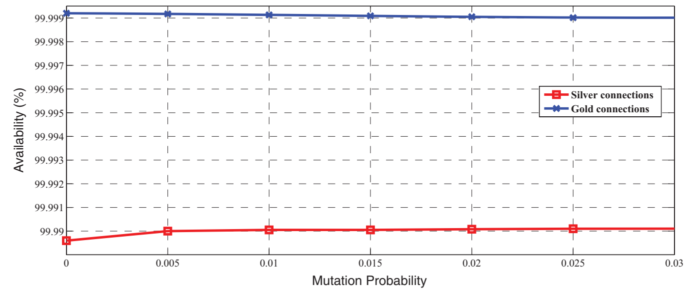

Fig. 2. Availability of gold and silver for $N_1 = 2$, $N_2 = 8$, and $M = 2$.

[4]. The availability of gold (resp. silver) is computed by evaluating U_1 (resp. U_2) for different values of the mutation probability P_{gs}. The obtained results are reported in Fig. 2. It is important to note in this respect that a mutation probability $P_{gs} = 0$ corresponds to the case where no mutations are possible and thus establishes a baseline for the mutation-based protection strategy. It is clear from Fig. 2 that after the introduction of mutation probability, the availability requirements of both gold and silver clients are met. A slight decrease in terms of the availability of gold connections is observed; however, by keeping the value of mutation probability below 0.03 the target availability of 99.999% can still be achieved. In addition, the results shown in Fig. 2 assert that a shared protection strategy without mutation probability violates the availability requirements of silver connections; in contrast, a mutation-based protection strategy whose implementation doesn't incur any additional cost has the ability to satisfy both silver and gold availability needs.

IV. Conclusion

This letter proposes to combine the rigid priority-aware shared protection scheme studied in the open literature with a parameter called mutation probability to form a more flexible protection strategy. The performance of the mutation-based strategy was studied with a view to obtaining the exact analytic expression of the availability per class of service resulting from the deployment of the proposed strategy.

The obtained numerical results proved that unlike the existing priority-aware shared protection scheme, the proposed scheme presents the advantage of improving the availability of low priority connections without severely compromising the availability of high priority clients.

References

[1] B. Mukherjee, *Optical WDM Networks*. New York: Springer, 2006.
[2] W. D. Grover, *Mesh-Based Survivable Networks*. Prentice Hall PTR, 2004.
[3] W. Fawaz, F. Martignon, K. Chen, and G. Pujolle, "A novel protection scheme for QoS aware WDM networks," in *Proc. ICC 2005*, pp. 122–127, May 2005.
[4] N. Bouabdallah and B. Sericola, "Intorducing a relative priority for the shared protection schemes," *IEEE Trans. Dependable and Secure Computing*, pp. 205–215, July-Sept. 2007.
[5] J. Zhang, K. Zhu, H. Zang, N. S. Matloff, and B. Mukherjee, "Availability-aware provisioning strategies for differentiated protection services in wavelength-convertible WDM mesh networks," *IEEE Trans. Networking*, vol. 5, no. 5, pp. 1177–1190, Oct. 2007.