Priority-aware Optical Shared Protection Coupled with Mutation Probability

Wissam Fawaz and Maurice Khabbaz

Abstract— **The next big challenge for optical network operators is to meet the diverse availability requirements of the various subscribed services through the adoption of appropriate protection strategies. One promising scheme that has been proposed in the open literature and that is presenting itself as a potential approach to dealing with this challenge is the priority-aware protection scheme. However, the priority-aware protection strategy suffers from a major limitation as it privileges the failed high priority connections taking no account of the failed low priority ones. As such, this paper proposes to combine priority-aware shared protection with a parameter called *mutation probability* thus giving birth to a more effective protection strategy.**

The mutation probability parameter expresses the likelihood that a low-priority connection be promoted temporarily to a higher priority level during its recovery. The proposed mutation-based protection strategy therefore allows optical operators to improve 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 paper by precisely calculating the connection unavailability that results from its deployment. A computational framework is proposed in this regard to highlight the merit that the mutation-based protection strategy has over the existing priority-aware protection scheme.

Index Terms: **Optical networks, Survivability, Performance evaluation.**

I. INTRODUCTION

The exponential unremitting data traffic growth is creating a whole new set of persisting incumbent challenges. Through the revolutionary Wavelength-Division Multiplexing (WDM) technology, optical networks have come to the rescue as fiber links are witnessing a tremendous increase in terms of their transmission capacity, which has already attained the order of several terabits per second [1]. Nonetheless, failures of optical network components (i.e. a fiber link, amplifier, transceiver, etc...) continue to weigh so heavily on optical operators as huge losses in both data and revenue are preventing them from keeping up with the competition for broadband traffic transport [2].

Under such circumstances, survivability together with its impact on network design become critically important to operators who, through resource-efficient shared protection schemes, try to restore failed connections using backup resources shared among a set of primary connections. *Classical shared protection* schemes [3], [4] for instance consider failed primary connections as equally important when contending for the use of the shared backup resources. With the advent of new services each having different availability requirements, these schemes are no longer adequate since they don't account for the various availability requirements of the failed primary optical connections during the course of recovery.

This limitation led the authors in [5], [6] to introduce the so-called *priority-aware shared protection* scheme, which proposes to restore failed primary connections in an order consistent with their respective priority levels. The priority of a failed connection is determined in this context by its availability requirement, so a more stringent requirement means a higher urgency level during restoration. However, continuously privileging higher priority connections under failure conditions severely degrades the quality of service perceived by low priority connections. This results in a situation where low priority connections become unable to meet their own required availability.

In view of this, there is an urgent need to improve the priority-aware scheme in such a way so as to smoothen the impact of high priority connections on lower priority ones. This should be done while making sure that the availability requirements of high priority connections are still being fulfilled. Inspired by these observations, this paper proposes a variant of the priority-aware protection scheme that aims at enhancing the performance of priority-aware protection by introducing a parameter called mutation probability. This parameter indicates the probability of treating a failed low priority connection as a high priority one during its recovery. With the introduction of the mutation probability parameter, low priority connections are given, from time to time, a higher priority with respect to the utilization of backup resources. This has the advantage of eliminating the unfair severe availability decrease experienced by low priority connections. Furthermore, by fine-tuning the value of the mutation probability parameter, optical operators are expected to be capable of increasing the availability of low priority connections while at the same time satisfying the availability requirements of higher priority ones.

The rest of the paper is structured as follows: in Section II, the proposed mutation-based shared protection strategy is described. Section III introduces a mathematical model that evaluates the unavailability resulting from the deployment of the proposed protection scheme for each category of connections. Illustrative numerical results are presented and analyzed in Section VI. Finally, section V concludes the paper.

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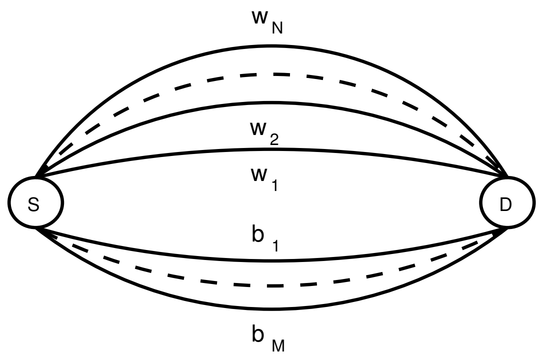

Fig. 1. N working paths sharing M backup paths.

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 Figure 1. For the sake of simplicity, connections are classified into 2 priority levels referred to as gold and silver respectively.

Let us assume that n_1 gold connections together with n_2 silver connections are broken down and thus compete for the use of the available backup resources. Under a priority-aware protection strategy, the n_1 failed gold connections are given not only a high restoration priority but also the capability of preempting previously recovered silver connections (if there are any and if necessary). As such, the n_1 failed gold connections are restored by the available backups prior to the n_2 failed silver connections. In the worst case, if the n_1 gold consume all of the available backups, the n_2 silver will be left with no backup resources and as a result become unavailable.

On the other hand, in case the proposed mutation-based protection strategy is deployed, the mutation probability, P_{sg}, comes into play as follows. With a probability P_{sg} each of the n_2 silver mutates from silver to gold and hence is granted a higher restoration priority. In this way, a failed silver connection experiences probabilistic transformation into gold, which in the event of transformation allows the failed silver to compete with the failed gold connections during restoration. Consequently, silver connections experience higher availability and are to some extent protected against the greediness of gold connections observed in the case of the existing priority-aware protection scheme. The higher the mutation probability is, the greater the improvement witnessed by silver connections would be.

The value of P_{sg} is nevertheless constrained by the need to respect the availability required by gold connections. This is especially true since a very high mutation probability may result in the violation of the availability requirements of gold connections. Therefore, optical operators are required to adjust the mutation probability parameter in a way that enables them to meet the availability needs of both silver and gold connections.

III. Unavailability Analysis: Mathematical Model

A mathematical model investigating the impact of mutation-based shared protection on the unavailabilities of gold and silver connections is delineated in this section. This mathematical study's intent is to prove that the mutation-based protection scheme has a better performance as compared to the existing priority-aware shared protection scheme.

Connection unavailability is widely defined as the probability that the connection is found in the broken down state at a random time in the future [7]. It can be computed statistically using the failure and repair rates as shown hereafter reflecting the proportion of time a connection is down during its entire lifetime.

A. Basic Assumptions

The mathematical study is based on the following classical assumptions:

- A connection is either available or unavailable.
- Different network components fail independently and the occurrence of failures lead to repair actions.
- Sufficient resources are available to repair simultaneously any number of failed connections. This is known in the literature as *unlimited repair* [8].
- For any component the operation time and the repair time are exponentially distributed with known mean values denoted respectively by $MTTF$ (Mean Time To Failure) and $MTTR$ (Mean Time To Repair). It is important to point out that $MTTF$ and $MTTR$ are calculated based on the statistics presented in [9], [10].

B. Model Definition

Let us consider N primary paths sharing M backup paths (*i.e.* , an M:N shared protection scheme). The N primary paths are divided into N_1 gold connections and N_2 silver connections with $N_1 + N_2 = N$. For sake of simplicity and without loss of generality, the mathematical model considers a case of special interest 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 $p = \frac{\mu}{(\lambda+\mu)}$ along with the same unavailability of $q = 1 - p = \frac{\lambda}{(\lambda+\mu)}$.

Existing priority-aware shared protection schemes privilege solely gold connections under failure conditions. Building on this observation, the protection strategy discussed in this paper proposes to improve the conditions of a failed silver connection by treating it as a gold connection according to a given mutation probability denoted by P_{sg}. The aim of P_{sg} is twofold: first, to improve the availability of silver connections; and, to make sure while doing so that the target availability of gold connections can still be achieved.

Let U_1 and U_2 denote respectively the unavailabilities of gold and silver connections. The computation of U_1 and U_2 requires that the stochastic process $\{X(t), t \geq 0\}$ whose general state is denoted by the 4-tuple (n_1, n_2, n_2', m) be considered. In this context, n_1 and n_2 are the number of failed gold and failed silver connections, n_2' is the number of failed silver that are subject to mutation and hence treated as gold during recovery, and m is the number of operational backup paths. Clearly, $\{X(t), t \geq 0\}$ is a continuous Markov process with a stationary probability given by:

$$Pr\{X=(n_1,n_2,n_2',m)\}=Pr\{n_1\}\cdot Pr\{n_2\}\cdot Pr\{n_2'|n_2\}\cdot Pr\{m\}$$

Since n_2' out of the n_2 failed silver connections mutate from silver to gold each with a probability P_{sg}, $Pr\{n_2'|n_2\}$ can be expressed as follows:

$$Pr\{n_2'|n_2\} = \binom{n_2}{n_2'} \times P_{sg}^{n_2'} \times (1-P_{sg})^{n_2-n_2'}$$

Given that p is the probability that a primary or a backup path fails, $Pr\{n_1\}$,$Pr\{n_2\}$, and $Pr\{m\}$ are given by:

$$\begin{aligned} Pr\{n_1\} &= \binom{N_1}{n_1} \times q^{n_1} \times p^{N_1-n_1} \\ Pr\{n_2\} &= \binom{N_2}{n_2} \times q^{n_2} \times p^{N_2-n_2} \\ Pr\{m\} &= \binom{M}{m} \times p^m \times q^{M-m} \end{aligned}$$

In what follows, closed-form expressions are derived for the unavailabilities of gold and silver connections under the proposed protection strategy.

C. Unavailability of a Gold Connection

A gold connection t_1 becomes unavailable when both of the following conditions are verified:

- A: The primary path of t_1 is broken down.
- B: t_1 cannot be restored by one of the m operational backup paths.

U_1, the unavailability of a gold connection, can thus be written as:

$$\begin{aligned} U_1 = & \sum_{(n_1,n_2,n_2',m)} Pr\{A, B, X = (n_1, n_2, n_2', m)\} \\ = & \sum_{n_1=1}^{N_1} \sum_{n_2=0}^{N_2} \sum_{n_2'=0}^{n_2} \sum_{m=0}^{M} Pr\{B|A, X\} \times Pr\{A|X\} \times Pr\{X\} \end{aligned}$$

Since the N_1 primary paths taken by gold connections have identical failure behavior, it can be easily shown that:

$$Pr\{A|X = (n_1, n_2, n_2', m)\} = \frac{n_1}{N_1}$$

As mentioned earlier, n_2' silver connections out of the n_2 failed silver are promoted to a higher urgency level and therefore act as gold connections during restoration. This implies that the total number of high priority connections that compete for the use of the m operational backup resources increases from n_1 gold to $(n_1 + n_2')$ gold and mutated silver. As a result, $(n_1 + n_2')$ failed connections are given the highest priority with respect to the use of the m operational backup paths. The restorability of a failed gold connection is thus strongly dependent on whether or not there are enough operational backup paths to accommodate all (n_1+n_2') failed high priority connections. Specifically, if $m \leq (n_1+n_2')$, then only m high priority connections out of the $(n_1 + n_2')$ failed ones can be restored. If on the other hand $m \geq (n_1 + n_2')$, then all $n_1 + n_2'$ failed high priority connections can be recovered. The previous discussion yields the following expression for $Pr\{B|A, X\}$:

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

To sum up, U_1 is given by the following expression:

$$U_1 = \frac{1}{N_1} \sum_{n_1=1}^{N_1} \sum_{n_2=1}^{N_2} \sum_{n_2'=0}^{n_2} \sum_{m=0}^{(n_1+n_2')\wedge M} n_1 \frac{n_1 + n_2' - m}{n_1 + n_2'} Pr\{X\}$$

D. Unavailability of a Silver Connection

The computation of the unavailability of a silver connection U_2 must take into account the possible transformation of a failed silver into a gold. It is therefore necessary to differentiate between two cases, namely the case where a failed silver undergoes mutation and the case in which a failed silver preserves its priority level. In fact, a failed silver

connection t_2 becomes unavailable when either of the following 2 pairs of events occur:

- (C : t_2 mutates from a low priority level to a higher one) and (D : The mutated t_2 is not restored).
- (E : t_2 does not mutate from low priority to a higher one) and (F : The non-mutated t_2 is not restored).

It follows that U_2 can be formulated as:

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

Given that the number of mutations taking place in the set of N_2 silver connections is limited to n_2', it can be easily proven that:

$$Pr\{C|X\} = \frac{n_2'}{N_2}$$

$$Pr\{E|X\} = \frac{n_2 - n_2'}{N_2}$$

.

Because D represents the case where t_2 turns into a gold, the principles are the same for both the calculation of $Pr\{D|C, X\}$, the probability that the mutated t_2 does not get recovered, and the calculation of $Pr\{B|A, X\}$, the probability that a gold connection is not restored. As such, $Pr\{D|C, X\} = Pr\{B|A, X\}$.

In addition, $Pr\{F|E, X\}$, the probability that t_2 is not restored given that t_2 does not go through mutation, can be obtained based on the following observations. In the context of the considered protection strategy, the (n_1+n_2') failed high priority connections can immediately seize operational backup paths regardless of the number of failed low priority connections there might be. Consequently, the $(n_2 - n_2')$ failed silver connections that don't experience mutation cannot gain access to backup resources until all $(n_1 + n_2')$ failed high priority connections have been recovered by the m operational backup paths.

In light of this, the restorability of the $(n_2 - n_2')$ non-mutated failed silver depends on both the number of operational backup paths (*i.e.*, m) and the number of failed high priority connections (*i.e.*, $(n_1 + n_2')$). In other words, if $m \leq (n_1 + n_2')$, then all m backups are reserved for the $(n_1 + n_2')$ high priority connections, and accordingly none of the $(n_2 - n_2')$ non-mutated silvers are restored. Moreover, if $(n_1 + n_2) > m > (n_1 + n_2')$, all $(n_1 + n_2')$ high priority connections are restored, and $m - (n_1 + n_2')$ out of the $(n_2 - n_2')$ non-mutated silvers are recovered. Finally, if $m \geq (n_1 + n_2)$, then the m operational backups are dedicated to the recovery of all $n_1 + n_2$ failed connections. As a consequence, $Pr\{F|E, X\}$ is given by:

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

After tying all of the pieces together, U_2 can be expressed as:

$$U_2 = \frac{1}{N_2}\left[\sum_{n_1=0}^{N_1}\sum_{n_2=1}^{N_2}\sum_{n_2'=0}^{n_2}\sum_{m=0}^{(n_1+n_2')\wedge M} n_2' \frac{n_1+n_2'-m}{n_1+n_2'} Pr\{X\}\right.$$
$$+ \sum_{n_1=0}^{N_1}\sum_{n_2=1}^{N_2}\sum_{n_2'=0}^{n_2}\sum_{m=0}^{(n_1+n_2')\wedge M} (n_2 - n_2') Pr\{X = (n_1, n_1', n_2, m)\}$$
$$\left.+ \sum_{n_1=0}^{N_1}\sum_{n_2=1}^{N_2}\sum_{n_2'=0}^{n_2}\sum_{m=n_1+n_2'}^{(n_1+n_2)\wedge M} (n_1+n_2-m) Pr\{(n_1, n_1', n_2, m)\}\right]$$

IV. Numerical Results

This section gauges the benefits of the mutation-based protection strategy by precisely evaluating its impact on the availability of gold and silver connections.

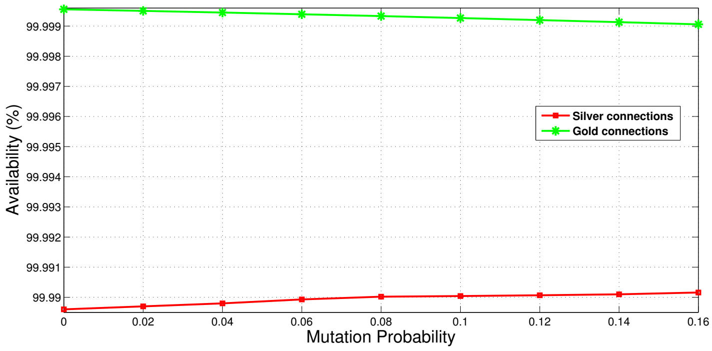

Fig. 3. Availability of Silver and Gold for $N_1 = 4$, $N_2 = 10$, and $M = 3$.

A. *First Scenario: a 2:7 shared protection scheme*

The proposed protection strategy is applied first in the context of a scenario consisting of $N_1 = 3$ gold, $N_2 = 4$ silver, and $M = 2$ backups. Following the guidelines presented in [9], [10], the repair rate μ is set to be equal to $1/12\, h^{-1}$, and a value of $1/600\, h^{-1}$ is used for the cut rate λ. Even though an optical network operator is expected to choose the availability associated with each priority level according to its business model, this paper opted for the availability requirements defined in [11] for illustration purposes. As such, a gold connection is assumed to have an availability requirement of 99.999%; Moreover, it is assumed that a silver connection requires an availability of 99.99%.

Figure 2 shows the availability of silver connections achieved in the context of the first scenario for different values of the mutation probability P_{sg}. It is important to note in this respect that a mutation probability $P_{sg} = 0$ represents the case where mutations are not possible and thus corresponds to the existing priority-aware protection scheme. The result obtained for $P_{sg} = 0$ establishes an important touchstone for the mutation-based protection strategy. Based on figure 2, it can be observed that silver connections presents higher availability in the case of the proposed protection strategy than in the case of the priority-aware protection scheme. This is especially true since silver connections become more available with the introduction of the mutation probability parameter.

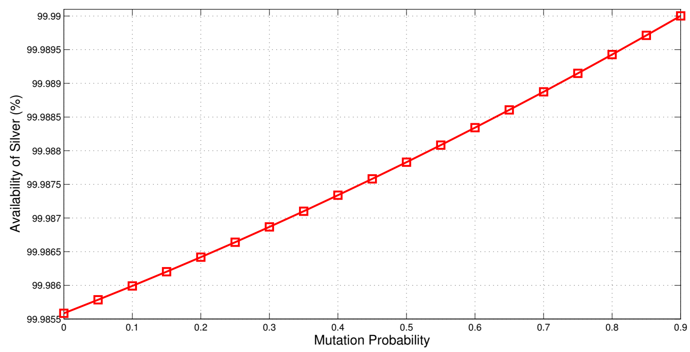

Fig. 2. Availability of Silver for $N_1 = 3$, $N_2 = 4$, and $M = 2$.

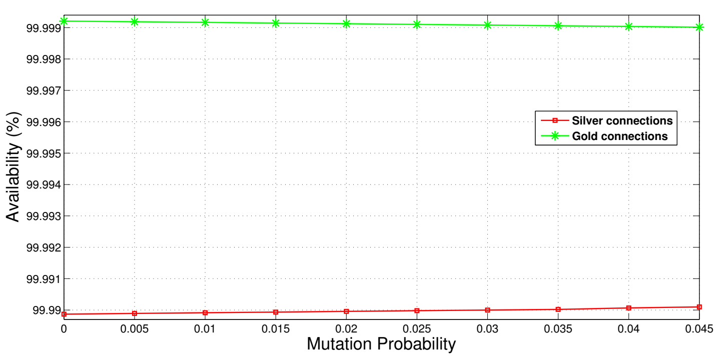

Fig. 4. Availability of Silver for $N_1 = 2$, $N_2 = 8$, and $M = 2$.

B. Second Scenario: a 3:14 shared protection scheme

In order to further underline the main interest behind the proposed protection strategy, a second scenario involving $N_1 = 4$ gold, $N_2 = 10$ silver, and $M = 3$ backups is examined. For this scenario, the cut rate λ is set to a reference value of $1/450\,h^{-1}$. Furthermore, the availability of gold (respectively silver) is computed by evaluating U_1 (respectively U_2) for different values of the mutation probability P_{sg}. The results related to the second scenario are reported in Figure 3. It is clear from figure 3 that after the introduction of mutation probability, the availability requirements of both gold and silver clients are met. Although gold connections appear to be less available under the mutation-based scheme than under the existing priority-aware scheme, the target availability level of gold is still respected. Figure 3 demonstrates also that by keeping the value of the mutation probability above 0.06 the availability of 99.99% imposed by silver connections can be achieved. In fact, for $P_{sg} = 0$ the availability of silver is below the baseline availability of 99.99%; however, as the mutation probability increases, the availability of silver grows and continues to grow until it reaches 99.99%. This proves that a priority-aware shared protection strategy without mutation probability violates the availability requirement of silver, while a mutation-based protection strategy has the ability to satisfy the availability needs of both silver and gold.

C. Third scenario: a 2:10 shared protection scheme

To further highlight the gain realized by the proposed protection strategy, the mutation-based strategy is implemented in the context of a third scenario encompassing $N_1 = 2$ gold, $N_2 = 8$ silver, and $M = 2$ backups. A value of $1/750\,h^{-1}$ is chosen for the cut rate λ in this regard. The results shown in figure 4 illustrate that silver connections can benefit greatly from the incorporation of the mutation probability into the existing priority-aware protection scheme. Though this gain comes at the expense of gold connections, the quality of service perceived by the gold connections is always maintained.

V. Conclusion

This paper proposes to improve the rigid priority-aware shared protection scheme studied in the open literature through the introduction of a parameter called mutation probability. The performance of the resulting mutation-based strategy was analyzed with a view to obtaining the exact analytic expressions for the unavailability of the different service classes.

The mutation-based protection scheme was found to be a flexible protection 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.

The introduction of the mutation-based protection strategy has a generic fundamental significance that goes beyond the specific context of optical networks. Indeed, the models studied in this paper can be applied not only to optical networks but also to general systems. Due to this generality, any further results that can be derived from the proposed computational framework have a potential significance for the design of survivable systems of any kind.

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