

# Survivability Strategies for PCE-based WDM Networks Offering High Reliability Performance

J. Ahmed, C. Cavdar, P. Monti, L. Wosinska  
Royal Institute of Technology (KTH), Stockholm, Sweden  
{jawwad, cavdar, pmonti, wosinska}@kth.se

**Abstract:** Two approaches based on backup reprovisioning and path restoration are proposed for dynamic failure recovery in survivable, PCE-based, WDM networks. Results show that proposed schemes can achieve high connection availability in double link failure scenarios.

© 2012 Optical Society of America

**OCIS codes:** (060.0060) Fiber optics and optical communications; (060.4250) Networks

## 1. Introduction

Achieving high reliability performance is a key issue in survivable wavelength division multiplexing (WDM) networks. This is particularly important for *mission-critical* dynamic applications, where it is crucial to avoid data losses as a consequence of *traffic-disruptions* caused by *failures*. Path-protection-based survivability approaches providing fast recovery from fiber cut have been widely studied in the literature and dedicated path protection (DPP) is the most common strategy utilized by network operators, mainly because of its fast *protection switching* times [1] as well as its ease of design and implementation. However, path protection schemes are typically designed to provide 100% survivability against single link failures, while the occurrence of multiple link failures will degrade the network reliability performance. Obviously, adding more backup paths (e.g., DPP 1:N) would improve the reliability but it is costly, thus not preferred by network operators. In this context, backup reprovisioning (BR) approaches can be used to *protect* existing connections and to improve network reliability performance [2][3]. The key idea is that after the first link failure, BR is attempted for the *vulnerable* connections, i.e. the ones left without protection. If any of these connections will be affected by a second failure they will have a *new backup path* available. However, BR may not always be effective in multiple link failure scenarios, with total downtime values (i.e., the recovery time, if/when backup resources are available, or alternatively the remaining portion of the service time during which the connection is down, if a connection cannot recover from a failure) that tend to increase drastically.

This work addresses this problem by involving path restoration (PR). We propose two failure recovery schemes, i.e., *DPP+PR* and *DPP+BR+PR* providing extra recovery options to vulnerable connections, thus maximizing the average connection availability. Time-efficient ILP models (i.e., with computation times < 50ms) are proposed to implement optimal failure recovery for the proposed schemes in a PCE (Path Computation Element)-based [4] WDM network. Results show that, in a double link failure scenario, the proposed schemes can achieve higher connection availability, and lower downtime (compared to BR-based approaches), while showing far lower blocking probability compared to protection strategies based on multiple dedicated backup paths (i.e., DPP 1:2).

## 2. Failure Recovery Schemes and ILP Formulations

This section briefly introduces the two proposed recovery schemes and the two strategies used for benchmarking followed by our time-efficient ILP formulations. It is assumed that up to two failures might simultaneously affect the network. In case of *DPP 1:2*, one dedicated path is always available for each possible failure. In *DPP+BR*, *DPP+PR*, and *DPP+BR+PR* one dedicated path is used for protection against one failure DPP 1:1, while either BR (in *DPP+BR*) or PR (in *DPP+PR*) is attempted for all connections left vulnerable by the first failure. With *DPP+BR+PR* BR is attempted for all connection left vulnerable by the first failure, while if a vulnerable connection is affected by the second failure, PR is attempted.

ILP formulations minimizing connection unavailability for the considered survivability schemes are now presented.

**Given:**  $G(N, E)$ , a physical topology consisting of a set of  $N$  nodes and  $E$  links.  $W$  is the maximum number of wavelengths supported on each link, and  $W_{xy}$  is the number of free wavelengths on link  $(x, y)$ .  $D$  is the set of connection requests fed to the ILP.  $\lambda_c$  represents a request  $c$  from source  $s$  to destination  $d$  where  $\lambda_c \in D$ .  $\lambda_c^p$  is equal to 1 if primary path for request  $c$  from source  $s$  to destination  $d$  has not failed.  $\lambda_c^{b1}$  is equal to 1 if the first backup path for request  $c$  from source  $s$  to destination  $d$  has not failed. Note that BR is triggered when either a primary or a backup fails ( $\lambda_c^p + \lambda_c^{b1} = 1, \forall \lambda_c \in D$ ).

**Variables:**  $p_{xy}$  is the number of wavelengths used by primary paths on link  $(x, y)$ .  $b1_{mn}$  is the number of wavelengths used by first backup paths on link  $(m, n)$ .  $b2_{ij}$  is the number of wavelengths used by second backup

paths on link  $(i, j)$ .  $p_{xy}^c$  is equal to 1 if request  $c$  from  $s$  to  $d$  passes through primary physical link  $(x, y)$ .  $b1_{mn}^c$  is equal to 1 if request  $c$  from  $s$  to  $d$  passes through physical link  $(m, n)$  of the first backup path.  $b2_{ij}^c$  is equal to 1 if request  $c$  from  $s$  to  $d$  passes through physical link  $(i, j)$  of the second backup path.  $A_c$  is equal to 1 if request  $c$  is successfully provisioned.

### ILP DPP Backup Reprovisioning (ILP\_DPP\_BR)

**Objective 1: Minimize**  $\alpha \cdot (|D| - \sum_{\forall c} A_c) + \beta \cdot \sum_{\forall (x,y)} p_{xy} + \gamma 1 \cdot \sum_{\forall (m,n)} b1_{mn}$

#### Constraints

$$\sum_{\forall x} p_{xk}^c - \sum_{\forall x} p_{kx}^c = \begin{cases} A_c, & k = d \\ -A_c, & k = s, \forall k, c, \exists \lambda_c^p = 0 \\ 0, & k \neq s, d \end{cases} \quad (1.1)$$

$$b1_{mn} = \sum_{\forall c, \exists \lambda_c^{b1} = 0} b1_{mn}^c, \forall (m, n) \quad (1.4)$$

$$\sum_{\forall x} b1_{xk}^c - \sum_{\forall x} b1_{kx}^c = \begin{cases} A_c, & k = d \\ -A_c, & k = s, \forall k, c, \exists \lambda_c^{b1} = 0 \\ 0, & k \neq s, d \end{cases} \quad (1.2)$$

$$p_{xy}^c = 0, \forall (x, y), \forall c, \exists (\lambda_c^{b1} = 1 \wedge b1_{xy}^c = 1) \quad (1.5)$$

$$b1_{xy}^c = 0, \forall (x, y), \forall c, \exists (\lambda_c^p = 1 \wedge p_{xy}^c = 1) \quad (1.6)$$

$$p_{xy} = \sum_{\forall c, \exists \lambda_c^p = 0} p_{xy}^c, \forall (x, y) \quad (1.3)$$

$$p_{mn} + b1_{mn} \leq W_{mn}, \forall (m, n) \in E \quad (1.7)$$

Constraints (1.1)-(1.2) are flow conservation constraints for the primary and backup paths, respectively. (1.3)-(1.4) compute the primary, and backup link load respectively. (1.5)-(1.6) ensure that a reprovisioned path is link disjoint from the path it is supposed to protect. Each link load value is bounded by (1.7).

### ILP DPP Path Restoration (ILP\_DPP\_PR)

**Objective 2: Minimize**  $\alpha \cdot (|D| - \sum_{\forall c} A_c) + \beta \cdot \sum_{\forall (x,y)} p_{xy}$

#### Constraints

$$\sum_{\forall x} p_{xk}^c - \sum_{\forall x} p_{kx}^c = \begin{cases} A_c, & k = d \\ -A_c, & k = s, \forall k, c \\ 0, & k \neq s, d \end{cases} \quad (2.1)$$

$$p_{xy} = \sum_{\forall c} p_{xy}^c, \forall (x, y) \quad (2.2)$$

$$p_{mn} \leq W_{mn}, \forall (m, n) \in E \quad (2.3)$$

Constraint (2.1) is used for flow conservation of the primary paths. (2.2) defines the primary link load. Each link load value is bounded by (2.3).

### ILP (DPP 1:2) Dynamic Provisioning (ILP\_DPPI2)

**Objective 3: Minimize**  $\alpha \cdot (|D| - \sum_{\forall c} A_c) + \beta \cdot \sum_{\forall (x,y)} p_{xy} + \gamma 1 \cdot \sum_{\forall (m,n)} b1_{mn} + \gamma 2 \cdot \sum_{\forall (i,j)} b2_{ij}$

**Constraints:** Constraint (2.1), (2.2) and

$$\sum_{\forall x} b1_{xk}^c - \sum_{\forall x} b1_{kx}^c = \begin{cases} A_c, & k = d \\ -A_c, & k = s, \forall k, c \\ 0, & k \neq s, d \end{cases} \quad (3.1)$$

$$b2_{ij} = \sum_{\forall c} b2_{ij}^c, \forall (i, j) \quad (3.4)$$

$$p_{xy}^c + b1_{xy}^c \leq A_c, \forall (x, y), \forall c \quad (3.5)$$

$$\sum_{\forall x} b2_{xk}^c - \sum_{\forall x} b2_{kx}^c = \begin{cases} A_c, & k = d \\ -A_c, & k = s, \forall k, c \\ 0, & k \neq s, d \end{cases} \quad (3.2)$$

$$p_{xy}^c + b2_{xy}^c \leq A_c, \forall (x, y), \forall c \quad (3.6)$$

$$b1_{xy}^c + b2_{xy}^c \leq A_c, \forall (x, y), \forall c \quad (3.7)$$

$$b1_{mn} = \sum_{\forall c} b1_{mn}^c, \forall (m, n) \quad (3.3)$$

$$p_{xy} + b1_{xy} + b2_{xy} \leq W_{xy}, \forall (x, y) \in E \quad (3.8)$$

Constraints (3.1)-(3.2) are for flow conservation for the first and second backup paths, respectively. (3.3)-(3.4) compute the backup link loads. (3.5)-(3.6)-(3.7) ensure that reprovisioned primary, and backup paths are mutually link disjoint. Each link load value is bounded by (3.8). In all objective functions parameter  $\alpha$  is assigned the highest value in order to maximize the number of reprovisioned/restored connections (i.e., minimize connection unavailability). On the other hand, parameters  $\beta$ ,  $\gamma 1$ , and  $\gamma 2$  are assigned, low values to minimize the required wavelength resources.

### 3. Simulation Setup and Numerical Results

Results are obtained using a Java-based discrete event-driven simulator running on a Red Hat Enterprise Linux workstation with 12 GB of memory and considering the NSF network topology [5], modified to become 3-edge-

connected. All fiber links are bidirectional, with 16 wavelengths per fiber. Each lightpath is assumed to require an entire wavelength bandwidth. The presented results are the average of 32 replications. The connection holding time is exponentially distributed with an average equal to 1 time-unit. Moreover, Poisson arrivals of connection requests are considered assuming a uniform load per node pair. The ILP models are solved using the *Gurobi Optimizer* 4.51 [6]. Time between failures occurring in the whole network is assumed to be exponentially distributed with an average equal to 2.5 time-units. Mean time to repair (*MTTR*) of a broken link is considered to be equal to 0.5 time-units. For dynamic DPP 1:1 connection provisioning, the heuristic presented in [7] is used. During failure recovery, the *original* primary path is *restored back* after a failed link is repaired.  $\alpha$ ,  $\beta$ ,  $\gamma_1$  and  $\gamma_2$  in the ILP objective functions are assumed to be 10,000, 1.0, 0.5 and 0.25 respectively, for the reasons explained in the previous section.

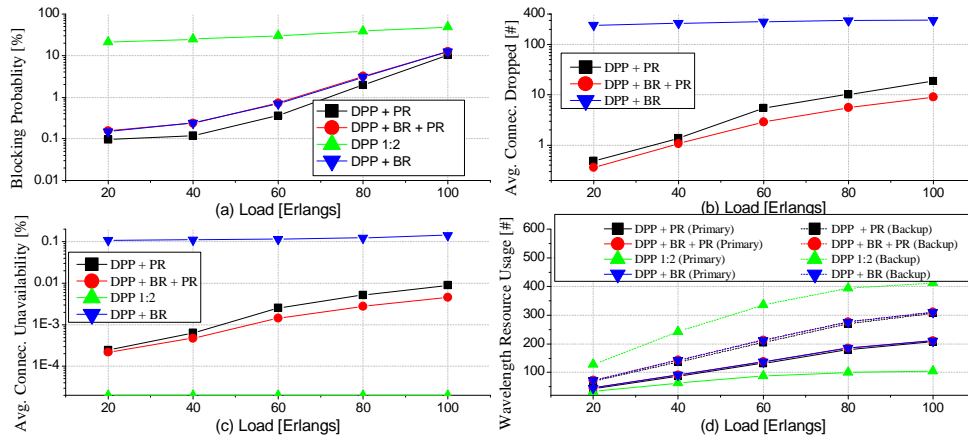


Fig.1. (a) Blocking Probability, (b) Avg. # of Dropped Connections, (c) Avg. Connection Unavailability, (d), Number of Used Wavelengths.

	DPP+PR			DPP+BR+PR			DPP+BR		
Load [Erlangs]	20	60	100	20	60	100	20	60	100
Downtime [time-units]	0.415	5.31	17.56	0.345	3.34	8.68	273	284	309

Table.1. Total connection downtime for different schemes.

Fig. 1(a) shows that the blocking probability (BP) is substantially higher for DPP 1:2 because it provisions three mutually link-disjoint paths (one primary and two backups) per each connection. It is also shown that DPP+BR+PR has slightly worse BP performance compared to DPP+PR because of the BR operations. DPP+PR drops almost twice as many connections as DPP+BR+PR (Fig. 1(b)), but still, both DPP+PR and DPP+BR+PR have a substantially fewer number of connections dropped than DPP+BR. Both proposed schemes show low connection unavailability values (Fig. 1(c)) which are worse than DPP 1:2, but way better than DPP+BR. Finally (Fig. 1(d)), DPP 1:2 requires significantly more backup resources as compared to the two proposed schemes. The total connection downtime values, in low load conditions, are very small for both the proposed schemes, but they grow more rapidly for DPP+PR at higher loads (i.e., 60-100 Erlangs). The reason is that DPP+BR+PR utilizes BR first to minimize the downtime, and PR is only attempted as a *last-resort* to avoid dropping a connection. On the other hand, the total connection downtime for DPP 1:2 can be neglected since it is equal to the switching time of an automatic optical switch, as a protection path for a provisioned connection is always guaranteed.

**4. Conclusion**

Two dynamic failure recovery schemes for PCE-based WDM networks (incl. ILP models) are proposed and evaluated against two benchmark schemes, i.e., DPP 1:2 and DPP+BR. In a double link failure scenario, the proposed schemes, i.e., DPP+PR and DPP+BR+PR, show a substantially better BP performance compared to DPP 1:2, while still being able to achieve significantly lower connection unavailability values than DPP+BR. Finally, DPP+BR+PR shows low total connection downtime values, and drops only half as many connections as DPP+PR in high network load conditions, an important performance criterion for network service providers.

**References**

[1] S. Ramamurthy, et. al., *IEEE/OSA Journal of Lightwave Technology*, 21, 870- (2003).  
 [2] L. Song, et. al., *IEEE/ACM Transactions on Networking*, vol.16, no.6, pp.1366-1377, December, 2008.  
 [3] J. Zhang et. al., *IEEE Journal on Selected Areas in Communications*, vol.24, no.8, pp.57-67, August, 2006.  
 [4] A. Farrel, et al., "A Path Computation Element (PCE) Based Architecture", IETF RFC 4655, August, 2006.  
 [5] X.-W. Chu, et al., in *Proc. of IEEE INFOCOM 2003*. San Francisco, CA, USA, April, 2003.  
 [6] Gurobi Optimizer, Online URL: <http://www.gurobi.com/>.  
 [7] J. Ahmed, et. al., in *Proc. of NOC/OC&I 2009*, Valladolid, Spain, June 2009.