Wavelength Continuity Constraint in Differentiated Reliability (DiR) WDM Rings

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Abstract— **The concept of *Differentiated Reliability (DiR)* was recently introduced by the authors to provide multiple reliability degrees (or classes) at the same network layer using a common protection mechanism, e.g., path switching. According to the DiR concept, each connection at the layer under consideration is guaranteed a minimum reliability degree, defined as the *Maximum Failure Probability* allowed for that connection. The reliability degree chosen for a given connection is thus determined by the application requirements, and not by the actual network topology, design constraints, robustness of the network components, and span of the connection.**

In the paper the DiR concept is applied to designing the Wavelength Division Multiplexing (WDM) layer of a ring network in which wavelength conversion is not available. To solve the routing and wavelength assignment problem at the WDM layer an efficient algorithm is proposed that resorts to reusable protection wavelengths while guaranteeing the required reliability degree of each connection. Lower bounds on the network bandwidth required by two approaches — respectively based on non-reusable and reusable protection wavelengths — reveal interesting properties of the DiR concept and the proposed algorithm.

I. INTRODUCTION

As e-commerce and e-business are heavily dependent upon the availability of communication resources, reliable communication networks are a must from the end user's viewpoint. Providing reliable communication is however expensive as additional spare resources must be provisioned in the network. Intuitively, a reasonable compromise would be to provision the strictly necessary redundancy of spare resources in the network to achieve a "satisfactory" reliability level, or degree.

Little is known, however, about the degree of reliability required at a given layer, that is, the level of reliability that the layer should provide to higher layers. Clearly, there is a trade-off between the degree of reliability that is offered by the layer and the cost of the resources required at that layer. A higher degree of reliability comes at higher cost. Another factor to consider is that the same network (or layer) is designed to support multiple services, and each service might require a distinct degree of reliability. For example, the WDM layer may support both SONET and IP layers, and may provide to each higher layer a different degree of reliability.

In a recent work [1] the authors have formally defined the aforementioned problem by introducing the so called *Differentiated Reliability* (or DiR for short) concept, according to which, multiple reliability degrees (or classes) are provided at the same layer using a common protection mechanism, e.g., path switching [2]. According to the DiR concept, each connection at the layer under consideration is assigned a Maximum Failure Probability (MFP) which is defined as the probability that the connection is unavailable due to the occurrence of a fault in the network. With DiR, the protection mechanism offers a variety of different MFP degrees. It is expected that the cost of the connection is inversely proportional to the chosen MFP degree.

The DiR concept offers the unique combination of the following advantages. The user (or upper layer) determines the desired MFP degree for each connection. Thus, in a multi-layer network, the lower layer may provide the above layers with the desired reliability degree, transparently from the actual network topology, design constraints, device technology and connection span. In addition, DiR allows to dynamically adjust the network configuration to take into consideration possible improvements of the network component's MTBF (Mean Time Between Failures) that may become available in some portion of the network, without affecting the reliability degree offered to the upper layers. In practical terms, improved MTBF of network components may allow the same network to support additional connections without affecting the guaranteed MFP of the already existing connections.

To explore its properties, in this paper the DiR concept is applied to cost effectively designing the Wavelength Division Multiplexing (WDM) layer of a bidirectional ring in which connections are set up in the form of paths of light, or lightpaths. To limit the complexity of the WDM layer, it is assumed that wavelength converters are not employed, thus each lightpath must be assigned the same wavelength across all the fibers of its path. A cost effective design — in terms of total wavelength mileage required at the WDM layer to support a given set of connections — is achieved by means of a proposed algorithm that solves the Routing and Wavelength Assignment (RWA) problem for each lightpath in a way that each connection MFP is satisfied. The algorithm is based on the principle that preemption of a less reliable connection to guarantee reliability of a more reliable connection is allowed if the resulting MFP degree still meets both connection requirements. This principle is ap-

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plied by *reusing* protection wavelengths — already assigned to more reliable connections — to carry less reliable connections. Numerical results show that, although sub-optimal, the wavelength mileage achieved by the proposed algorithm is close to a lower bound derived for the case of reusable protection wavelengths. A second lower bound, computed in the case of non-reusable protection wavelengths — in which connection preemption is not allowed — indicates that the benefits of wavelength reuse increase as the reliability degree required by the connections decreases.

II. DiR-Based WDM Ring

First the RWA problem in the DiR-based WDM ring without wavelength converters is defined, then an efficient algorithm that sub-optimally solves the problem is briefly described.

A. The RWA Problem in DiR-Based WDM Ring

This subsection describes the assumptions made and defines the DiR optimal design problem.

It is assumed that a set of connection demands is given and must be routed across the ring. A *connection demand* consists of one or multiple lightpaths[1], that need to be established between two nodes. Each connection demand is assigned a required MFP that must be met by the protection mechanism at the optical layer. Only one protection mechanism is available at the optical layer to achieve the demand required MFP. This requirement appears to be necessary to provide feasible network management as opposed to complex management handling of multiple concurrent recovery actions that take place in the event of a network element failure. The protection mechanism considered in this paper is the 1 : 1 path protection applied to lightpaths. With this protection mechanism, a *working lightpath* is assigned a route-disjoint *protection lightpath* that may be alternatively used if the working lightpath fails to work. Even though the ring does not have wavelength conversion capabilities, the wavelength continuity constraint does not prevent the working and protection lightpath to be assigned distinct wavelengths.

First, the set of multiple *reliability classes* is introduced. A reliability class, c, is characterized by a connection maximum failure probability $MFP(c)$, which indicates the maximum acceptable probability that, upon a network element failure, a connection in that class will not survive despite the optical layer protection[2].

Connection demands are assigned to classes according to their required MFP. Traffic demands in higher requirement classes, i.e., lower MFP, are those with the most stringent requirements in terms of recovery speed and need to be restored at the optical layer (e.g., voice traffic), as opposed to traffic demands in lower classes that may also be recovered by means of the (relatively slower) IP restoration mechanisms.

The WDM ring topology is modeled as a graph $G(\mathcal{N}, E)$. Set $\mathcal{N}$ represents the network nodes and link set E represents the WDM ring lines connecting physically adjacent nodes. Each link in E is characterized by the available wavelength set and a number pair: link cost and link failure probability.

The available wavelength set represents the set of wavelengths that are not (yet) used and can be employed to set up a lightpath.

The link cost represents the cost of routing a lightpath on that link, i.e., using a wavelength. For example, in the paper the link cost is set equal to the link length, thus it is assumed that the cost of routing a lightpath on that link is proportional to the link length.

The link failure probability is the probability that the considered link is faulted under the condition that a single network line fault has occurred in the ring[3]. The link failure probability is estimated on the basis of available failure statistics of the employed optical components. First, the probability of having a single fault in the network is estimated. Once this value is known, every link fault probability is normalized to the probability of having a single fault in the network. We define $P_f(i,j)$ as the failure probability of link (i,j), given the occurrence of one fault in the network. A uniform distribution of faults among links, would result then in $P_f(i,j) = \frac{1}{|\mathcal{N}|} \;\; \forall (i,j) \in E$.

To implement the DiR concept, the 1 : 1 path protection scheme is modified as follows[4]. A lower class working lightpath may be routed on already provisioned protection wavelengths if the wavelength continuity constraint is satisfied, thus improving use efficiency of network resources. Consequently, in case of a link failure, a higher class connection may preempt a lower class connection if the latter is using protection resources dedicated to the former. This mechanism affects the connection failure probability of the lower class connection due to its preemption. From a lower class connection viewpoint, preemption is equivalent to a fault that disrupts its working lightpath without the possibility to resort to a protection lightpath. For each connection, we thus define the connection failure probability as the sum of the failure probabilities of its unprotected links plus the probability of "virtual" failure due to preemption. It is assumed that the connection failure probability is determined only by the link failure probabilities and it does not depend on the particular wavelength assigned to the connection.

The objective of the DiR problem is to determine the routing, the wavelength assignment, and the resources used by each lightpath request in order to minimize the ring

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[1] A lightpath is a path of light between a node pair, whose bandwidth equals the wavelength bandwidth.

[2] The concept of reliability class can be easily generalized to multiple failures.

[3] The analysis presented here is based on the assumptions that only single (line) faults may occur. However, the proposed technique can be extended to handle concurrent faults of varying natures, including node faults.

[4] Notice that provisioned protection wavelengths are unused in absence of network failures.

total *wavelength mileage* — more generally, the network cost — subject to guaranteeing the requested reliability degree ($MFP(c)$) of each traffic class c.

B. The Difficult-Reuse-First Algorithm

This section presents an efficient greedy algorithm that may be used to sub-optimally solve the DiR design problem in WDM rings without any wavelength conversion capability. The name of the algorithm is Difficult-Reuse-First (DRF) to indicate that, prior to being routed, demands are sorted considering how difficult it is for the corresponding working lightpaths to achieve reuse of protection wavelengths. Lightpaths that are more difficult in that regard, are routed first, thus giving them better chance to achieve a more efficient wavelength reuse.

The DRF algorithm is based on two observations.

1. Due to the topological layout of bidirectional ring, only two disjoint routes exist between any node pair. Routing is thus a binary problem and each demand that requires protection must employ both routes, one for the working lightpath and the other for the protection lightpath.
2. When the reliability degree requested for the connection cannot be achieved using the already provisioned wavelengths, an additional wavelength must be added to the ring. Under this circumstance, irrespective of the routing (clockwise or counterclockwise) chosen for the working (protection) lightpath, one wavelength is used on every line of the ring. The cost (working and protection) for setting the connection thus equals the cost of adding a wavelength along the whole ring perimeter.

The algorithm is an enhanced version of the algorithm presented in [1] to design WDM ring in presence of wavelength converters. The algorithm in [1] is modified as follows.

The following definitions are used in the description of the DRF algorithm. The failure probability of a path is given by the sum of the failure probabilities of the links along the path. The failure probability of a path depends only on the links it goes through, it does not depend on the particular wavelength employed. The minimum failure probability between two nodes, mfp_{sd}, is the minimum between the failure probability of the clockwise and the counterclockwise path. Let $MFP(c)$ be the maximum acceptable failure probability for connection demands in class c.

The algorithm is organized in 7 steps.

Step 1. Connection demands are classified using two sets: the set of demands that require some degree of protection and the set of demands that do not require protection. Demand of class c from node s to node d belongs to the former set if $mfp_{sd} > MFP(c)$. It belongs to the latter set otherwise.

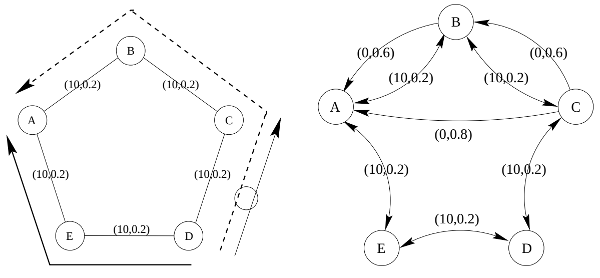
Step 2. The working lightpath for each demand in the former set is routed using the shortest path in terms of number of links. The protection lightpath is routed using the opposite direction. Shortest path in terms of number of links is chosen for the working lightpath to yield the maximum number of protection wavelengths in the ring that may be reused by the algorithm at some later step. The working wavelength is chosen according to the least loaded wavelength algorithm [3]. This algorithm chooses the least used wavelength along the chosen route. Notice that these connections have failure probability equal to 0, as they all survive any single fault in the ring.

Step 3. The demands in the latter set are sorted according to increasing values of the difference $X = (MFP(c) - mfp_{sd}) \geq 0$ where c, s, and d are, respectively, the class, the source, and the destination of the demand. Let S_X be the set of such sorted demands. Value X indicates the excess of reliability offered to the demand if a working dedicated wavelength were added to each link of the the path with minimum failure probability mfp_{sd}. Since the excess of reliability is not necessary, the algorithm looks for ways to reuse some of the already provisioned protection wavelengths in place of the added dedicated wavelengths. When a protection wavelength is used in place of an added wavelength, the reliability excess of the demand is reduced due to the potential preemption of that wavelength. Notice that the reliability excess must not be reduced below zero, otherwise the required reliability degree required by the demand is not met.

Intuitively, smaller values of X correspond to demands with lower probability to achieve reuse of protection wavelengths. In order to achieve a more efficient wavelength reuse — which in turn corresponds to a lower total network cost — demands having smaller X are routed first, hence the name of the algorithm.

Step 4. The demand in set S_X with the smallest value of X is considered for routing. Prior to routing the demand, an auxiliary graph $G'(\mathcal{N}, E')$ is built. $\mathcal{N}$ is the set of network nodes, E' is the union of set $E \in G$ and set E_p. The latter is the set of links that represent the provisioned protection lightpaths (or portions of them) not yet reused. Set E_p is constructed as follows. Let s be the source node, d the destination node and $I = \{n_1, n_2, \ldots, n_k\}$ the ordered set of intermediate nodes of a protection lightpath. Every time a protection lightpath is added to the ring, link (s, d), all links (s, n_i), where $n_i \in I$, all links (n_i, d), where $n_i \in I$, and all links (n_i, n_j), where $n_i, n_j \in I$ and $i < j$, are added to E_p. Link (s, d) represents the entire protection lightpath. Any other link represents only a portion of the protection lightpath. When multiple protection lightpaths share the same source, destination pair and route, the set of corresponding links added to the auxiliary graph is derived at once, keeping track of the multiple wavelengths assigned to the protection route.

Each link $l \in E'$ is assigned an set of available wavelengths and a pair of values: a cost and a failure probability. Link set and value pair are derived as follows. For each link in $E' \cap E$ the set contains all wavelengths that are not (yet) used by a working or a protection lightpath routed on such link. The link value pair is represented by the length of the associated line (cost is assumed to be proportional to the line length) and its original failure probability, respectively. For each link in E_p the set contains all wavelengths assigned to the corresponding protection lightpath that are not (yet) reused by some working lightpath. Every link in E_p is assigned zero cost, as routing on any such link represents reuse of an already provisioned protection lightpath (or portion of it). Each link in E_p is assigned a failure probability that is the sum of two terms: the failure probability of the working lightpath associated with the protection lightpath (or portion of it) represented by the link, i.e., the probability of preemption; plus the failure probability of the represented protection lightpath (or portion of it).



(a) Original graph (b) Auxiliary graph

Fig. 1. New links in the auxiliary graph graph

Figure 1(a) represents the auxiliary graph obtained from the ring shown in Figure 1(b). In Figure 1(a) the original topology graph with two working connections — the solid lines — is shown. Links are assigned two values that represent, respectively, the cost of the network line and the network line failure probability. In the example, only one wavelength is considered. For each link the available wavelength set either contains one wavelength or is empty. It is assumed that connection demand from node D to node A requires protection, represented by the dotted line in the figure. Connection demand from node D to node C belongs to a lower requirement reliability class and thus it may reuse some of the protection wavelengths provisioned for the former demand. The corresponding auxiliary graph is shown in Figure 1(b). Set E' consists of the union of link set E and the additional links (C, B), (B, A), and (C, A) (set E_p), that represent, respectively, the possibility to reuse protection wavelengths on the original graph links (C, B), (B, A), and the concatenation of (C, B) and (B, A). The auxiliary graph does not contain link (D, C), since its available wavelength set is empty, i.e., the protection wavelength on that link is already reused. Notice that added link (C, A), which represents a portion of the protection lightpath associated with the working lightpath from node D to node A, has failure probability given by the sum of three terms: the probability that the working lightpath from D to A is rerouted because of a line fault (0.4); the probability that line (C, B) is faulted (0.2); and the probability that line (B, A) is faulted (0.2).

Step 5. The demand under consideration is routed using the Dijkstra shortest path algorithm [4] applied to the auxiliary graph. The shortest path algorithm is slightly modified to take into account the wavelength continuity constraint. Each shortest path is assigned an available wavelength set which represents the set of all wavelengths that may be employed to route a lightpath along such path. Furthermore, while running the shortest path algorithm, at every intermediate step, the label of each node i — neighbor of the minimum distance node i_{min} — is updated only if set W_{av}, resulting from the intersection between the available wavelength set of the link connecting i_{min} to i and the available wavelength set of the path from the source to i_{min} is non-empty. If $W_{av} \neq \emptyset$, then the available wavelength set of the path from the source to i is set equal to W_{av}.

The auxiliary graph link weight l_{ij}^{aux} used by the shortest path is computed as a linear combination of the link cost (l_{ij}) and the link failure probability ($P_f(i, j)$). The linear combination is controlled by parameter a as follows: $l_{ij}^{aux} = a \cdot l_{ij} + (1 - a) \cdot P_f(i, j)$. When $a = 1$ the algorithm returns the shortest path in terms of mileage, when $a = 0$ the algorithm returns the shortest path in terms of failure probability, i.e., the most reliable path.

By varying a, a dichotomic search is performed. Let $a_{max} = 1$ and $a_{min} = 0$. The shortest path algorithm is run using the mean value $a = a_{int} = (a_{max} + a_{min})/2)$. Let $pf_{a_{int}}$ be the failure probability of the path so found. If $pf_{a_{int}}$ is greater than the MFP requested for the demand a_{max} is set equal to a_{int}. If $pf_{a_{int}}$ is smaller than the MFP, a_{min} is set equal to a_{int}. These steps are iterated until $pf_{a_{max}} \leq MFP$.

Once the shortest path is found, the working lightpath is assigned the least loaded wavelength [3] found in the available wavelength set associated with the path.

Step 6. Wavelengths assigned to the demand under analysis are provisioned and the corresponding demand is removed from set S_X.

Step 7. The status of the provisioned protection wavelengths is updated taking into consideration possible reuse. Notice that such update may result in changes of the auxiliary graph. The algorithm returns to step 4 until set S_X is emptied.

III. LOWER BOUNDS ON TOTAL WAVELENGTH MILEAGE

Two lower bounds on the total wavelength mileage required by the DiR-based ring are derived: Λ, when protection wavelength reuse is not allowed and Λ_r when protection wavelength reuse is allowed. The two bounds are derived under the simplified scenario of uniformly distributed line failure probability and line unit length, i.e., unit length is assumed for every ring line. Generalization of the bounds to uneven line failure probability and general line lengths is straightforward.

Derivation of the bounds is based on the observation that in case of uniform line failure probability, the more reliable route is the shortest path. Those connections that do not meet their reliability requirement along the shortest path need protection. Bounds are derived assuming full wavelength conversion capability at every node.

The following parameters are used in the derivation of the bounds. Let $t^c_{(i,j)}$ be the set of lightpath requests associated with the connection demands of class c between node pair (i, j). Connection demands are divided into two sets: T^c_p is the set of demands in class c that need protection, T^c_{np} is the set of demands in class c that do not need protection to meet their required reliability degree and may reuse protection wavelengths.

A. Lower Bound for Non-reusable Protection Wavelength

For every lightpath request in $t^c_{(i,j)}$ whose connection demand is in set T^c_p one wavelength must be added along the ring perimeter (working and protection paths). For every lightpath request in $t^c_{(i,j)}$ whose connection demand is in set T^c_{np} one wavelength must be added along the shortest path between node i and j. Let $SP_{(i,j)}$ be the length of the shortest path between node i and j

The mileage, Λ_c, required by reliability class c is then:

$$\Lambda_c = \left(\sum_{t^c_{(i,j)} \in T^c_p} |\mathcal{N}| \cdot |t^c_{(i,j)}| \right) + \left(\sum_{t^c_{(i,j)} \in T^c_{np}} SP_{(i,j)} \cdot |t^c_{(i,j)}| \right) \quad (1)$$

The total required wavelength mileage is therefore:

$$\Lambda = \sum_c \Lambda_c \quad (2)$$

From Equation (1) the average wavelength mileage per lightpath in class c is then computed as:

$$N_c = \frac{\Lambda_c}{\sum_{i,j} |t^c_{(i,j)}|} \quad (3)$$

B. Lower Bound for Reusable Protection Wavelength

In the case of protection wavelength reuse the derivation of the lower bound is based on the observation that the connection failure probability is the sum of two terms: the failure probability of the working path plus the preemption probability of the working path caused by a connection with higher reliability degree. The bound is derived assuming that protection wavelengths can be *arbitrarily* moved around the ring perimeter in order to maximize the reuse factor.

Three vectors $W_c[k]$, $P_c[k]$, and $P[k]$, $k = 1, \ldots, |\mathcal{N}|/2$, are defined. The $k-th$ entry of vector W_c is the set of lightpath requests $t^c_{(i,j)}$ that have $SP_{(i,j)} = k$. Notice that set $W_c[k]$ contains lightpaths whose connection demands are in either set T^c_p or set T^c_{np}. The failure probability of these lightpaths is $\frac{k}{\mathcal{N}}$ (without considering protection). The $k-th$ entry of vector P_c is the set of protection lightpaths provisioned to connection demands in class c, that are available for reuse and have preemption probability equal to $\frac{k}{|\mathcal{N}|}$. The $k-th$ entry of array P is the set of all protection lightpaths that are available for reuse and have preemption probability equal to $\frac{k}{\mathcal{N}}$, i.e., $P = \cup_c P_c$. Let $\|W_c(k)\|$, $\|P_c(k)\|$, and $\|P(k)\|$ be, respectively:

$$\|W_c(k)\| = \sum_{i,j:SP_{(i,j)}=k} \left(|t^c_{(i,j)}| \cdot SP_{(i,j)} \right) \quad \forall k = 1..\frac{|\mathcal{N}|}{2} \quad (4)$$

$$\|P_c(k)\| = \sum_{\substack{i,j \,:\, SP_{(i,j)} = k \\ t^c_{(i,j)} \in T^c_p}} \left((|\mathcal{N}| - SP_{(i,j)}) |t^c_{(i,j)}| \right) \quad \forall k = 1..\frac{|\mathcal{N}|}{2} \quad (5)$$

$$\|P(k)\| = \sum_c \|P_c(k)\| \quad \forall k = 1..\frac{|\mathcal{N}|}{2} \quad (6)$$

Working lightpaths in $W_c[k]$ may reuse protection only if the additional failure probability introduced by the preemption mechanism is smaller than $MFP(c) - (\frac{k}{|\mathcal{N}|})$. Working connections whose failure probability along the shortest path is closer to $MFP(c)$ have a more stringent requirement on the preemption probability, thus in order to maximize the probability of wavelength reuse, they need to be considered first in the computation of the bound. Furthermore, in order to save wavelengths with lower preemption probabilities for connection demands with more stringent reliability requirements, reuse of protection wavelengths with preemption probability exactly equal to $MFP(c) - (\frac{k}{|\mathcal{N}|})$ must be tried first. If protection wavelengths with that preemption probability are not available, protection wavelengths with lower preemption probability are taken into consideration for possible reuse.

Based on the above observations the mileage of reused protection wavelengths is always bounded from above by *reuse*, computed as follows:

```
$reuse = 0$
for $p = 1 : |\mathcal{N}|$
  for $m = \frac{|\mathcal{N}|}{2} : 1$
    for each reliability class $c$
      $k = (MFP(c) \cdot |\mathcal{N}|) - p$
      if $((k + m < MFP(c))$ AND $(k > 0)$ AND $(k \leq \frac{|\mathcal{N}|}{2}))$
        if $((\|P(m)\| - \|W_c(k)\|) > 0)$
          $reuse = reuse + \|W_c(k)\|$
          $\|W_c(k)\| = 0$
          $\|P(m)\| = \|P(m)\| - \|W_c(k)\|$
        else
          $reuse = reuse + \|P(m)\|$
          $\|P(m)\| = 0$
          $\|W_c(k)\| = \|W_c(k)\| - \|P(m)\|$
        endif
      endif
    endfor
  endfor
endfor
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The lower bound on the total wavelength mileage required by the DiR-based ring in case of protection wavelength reuse is then:

$$\Lambda_r = \Lambda - reuse \quad (7)$$

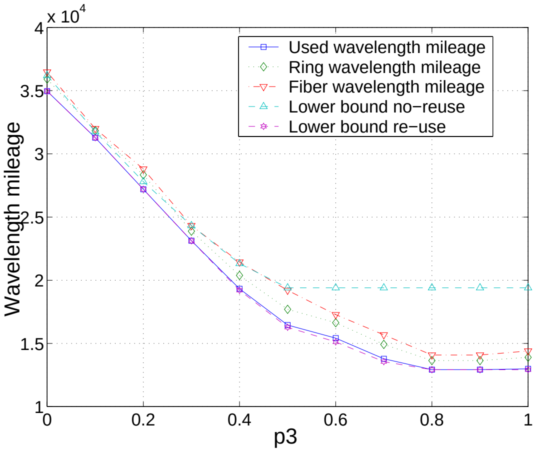

Fig. 2. Wavelength mileages for $p_1 = 0.1$ and $p_2 = 0.3$

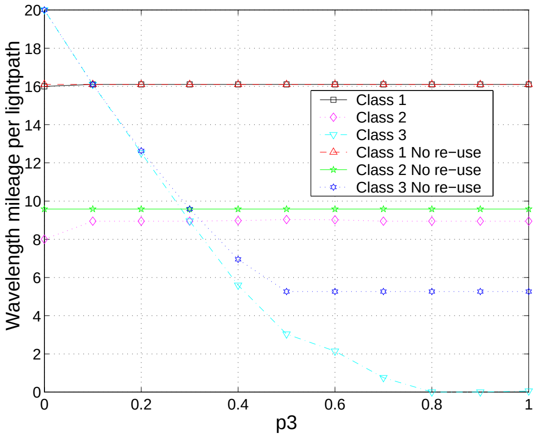

Fig. 3. Average wavelength mileage per lightpath when $p_1 = 0.1$ and $p_2 = 0.3$

IV. Performance Results

The DRF algorithm is tested using a ring topology that comprises 20 nodes connected by equal length lines of 1 mile each, i.e., each line has a unit cost. Fibers carry up to 16 wavelengths. Each network line represents multiple fibers. The actual total number of fibers per line is computed after the RWA algorithm has been run. At intermediate nodes wavelength conversion is not allowed, but lightpaths, as long as the wavelength continuity constraint is fulfilled, may be switched to any available output fiber. It is assumed that failure probability is evenly distributed among the network lines, i.e., $P_f(i,j) = 1/20 \forall (i,j) \in E$. Connection demands are divided into three classes.

- Class 1 demands require $MFP(1) = p_1$.
- Class 2 demands require $MFP(2) = p_2$.
- Class 3 demands require $MFP(3) = p_3$.

In all experiments the DRF algorithm was run on a Linux-PC pentium $450 MHz$, requiring a computational time in the order of few minutes.

Three network costs are computed: the *used wavelength mileage* required to fulfill all demands $t^c_{(i,j)}$ while providing the required reliability degree $MFP(c)$; the *ring wavelength mileage*, i.e., the wavelength mileage required by the DiR-based ring when the number of wavelengths is kept constant within each direction of propagation of the signal; the *fiber wavelength mileage*, i.e., the wavelength mileage required by the DiR-based ring when the number of fibers is kept constant within each direction of propagation of the signal and all carried wavelengths (used or not) are accounted for.

Two traffic scenarios are considered: uniform and non-uniform.

In the uniform traffic study, class 1 demands require one lightpath between each node pair, class 2 demands require two lightpaths between each node pair, and class 3 demands require three lightpaths between each node pair.

Figures 2 and 3 present results obtained setting $p_1 = 0.1$ and $p_2 = 0.3$, while p_3 varies in the interval $[0, 1]$.

Fig. 2 shows the three network costs and the two bounds obtained from Equation (2) and Equation (7). As expected the total network cost decreases as the required reliability degree becomes less stringent for class 3 demands. The used wavelength mileage obtained with the DRF algorithm is always less than the lower bound computed for the DiR ring without protection wavelength reuse. The mileage reduction obtained with wavelength reuse is more pronounced when the reliability degree of class 3 is lower. For $p_3 \geq 0.8$ the bound with protection wavelength reuse equals the cost of the same ring network in which shortest path routing is used and no protection is provisioned. In all cases, the used wavelength mileage obtained by the DRF algorithm is within few percents of the lower bound computed for the wavelength reuse case.

Fig. 3 plots the average wavelength mileage per lightpath for each reliability class. Reused protection wavelengths are counted only once. The plots show that the average cost of a connection is inversely proportional to $MFP(c)$ — class c maximum failure probability. For comparison, the figure plots the curves obtained by the DRF algorithm and the bound obtained from Equation (3), in which protection wavelength reuse is not allowed. Fig. 3 shows that when $p_1 = 0.1$, $p_2 = 0.3$, and $p_3 \geq 0.8$, it is possible to accommodate lightpaths that belong to class 3 without any additional cost thanks to the wavelength reuse mechanism.

A non-uniform traffic scenario is investigated next. For each class a connection demand matrix is randomly generated. Entries of class 1 demand matrix are uniformly generated numbers in the interval $[0, 2]$. Entries of class 2 demand matrix are uniformly generated numbers in the interval $[0, 4]$. Entries of class 3 demand matrix are uniformly generated numbers in the interval $[0, 6]$. Each entry of each matrix is then multiplied by a 50 factor with probability P_{nu}.

Fig. 4 plots results obtained for varying non-uniform traffic scenarios. Curves show the wavelength mileages and the bounds computed from Equation (2) and Equation (7) versus P_{nu}. From left to right, the amount of traffic sta-

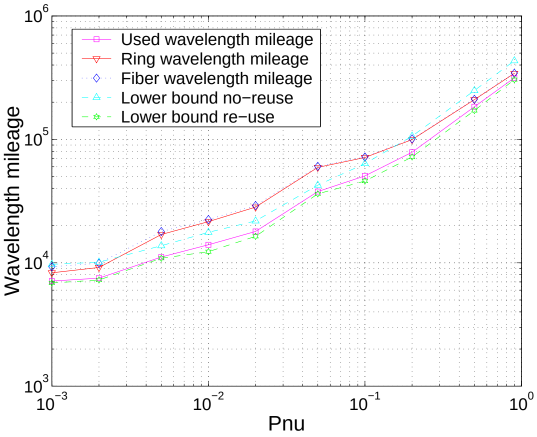

Fig. 4. Wavelength mileages for non-uniform traffic and $p_1 = 0.1$, $p_2 = 0.3$, and $p_3 = 0.6$

tistically increases, with the most unbalanced traffic cases when P_{nu} is away from values 0 and 1. The curves show that the DRF algorithm reaches satisfactory results for all traffic distributions. Also in this set of experiments, the bound obtained using Equation (7) is only few percents better than the result obtained by the algorithm.

V. Conclusions

The paper applied the recently proposed concept of Differentiated Reliability (DiR) to designing WDM ring without wavelength converters. According to DiR, classes of connections are differentiated based on their required individual degree of reliability. The proposed concept enables to differentiate traffic flows in classes without regard for network topology, equipment MTBF, and most importantly connection span, both in terms of line hops and mileage.

An efficient algorithm was proposed to solve the routing and wavelength assignment problem in the DiR-based WDM ring. The objective of the algorithm is to minimize the required total wavelength mileage taking advantage of protection wavelength reuse allowed by the DiR paradigm. It was experimentally demonstrated that under various traffic configurations the algorithm reaches wavelength mileages within few percents from a lower bound. Results show the effectiveness of the proposed concept, and confirm the intuition that a higher reliability comes at a higher cost.

Beside the optical layer discussed in the paper, the DiR concept may find other applications in a variety of network layers, including the Multi Protocol Label Switching (MPLS) layer.

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