Path Protection in Impairment-Aware WDM Networks

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Abstract

One of the major problems facing e-commerce, e-government and Internet users, in general, is the reliability of data transfers across the network. The installation of optical networks has certainly helped to increase the speed and reliability of data communication but network survivability still remains a challenge. Imagine what would happen in the banking sector if transactions cannot be processed because of poor network performance. The cost of providing separate systems with massive redundancies has been excessively high. As such, a number of researchers have tried to solve the problem of network reliability and, in particular, how to improve network performance in impairment-aware WDM networks. This survey is about their research.

Contents

1 INTRODUCTION

1.1 The scope of the survey

This survey concerns research which attempts to solve the problem of how to improve network performance. In particular, how to improve reliability in impairment-aware WDM networks.

1.2 Why the survey is important

If the problem of improved network performance is solved, it would enable more efficient and reliable transmission of data over optical networks.

1.3 The resources used to identify related research

Relevant research papers were found by searching Google Scholar with the keywords "path protection", "protected path" OR "protected-path", "impairment aware" OR impairment-aware, and WDM. Various keywords and author names were also used to search the ACM Digital Library, IEEE Xplore and Lecture Notes in Computer Science, through the University of Windsor Leddy Library.

It should be noted that some of the papers were not caught in the above-mentioned dragnets and were only found as a result of searching for the references given by selected papers.

1.4 Research papers identified

Thirteen (13) journal papers and sixteen (16) conference papers which are closely related to the survey were identified. They are listed in the bibliography.

1.5 Papers that were used as the basis of the survey

Eleven (11) papers were chosen as the basis of this survey. There are six (6) journal papers and five (5) conference papers. The reasons for choosing them are as follows:

[Yang et al, April 2005] was chosen because it is a journal paper that is exactly on topic and was cited on three (3) of the list of eleven papers. It is also among the first set of works published on this topic.

[Zhai et al, June 2007] was chosen because it is exactly on topic conference paper that was cited on three (3) of the list of eleven papers.

[Wang and Li, July 2007] was chosen because it is an exactly on topic journal paper and was cited on one (1) of the list of eleven papers.

[Markidis and Tzanakaki, 2008] was chosen because it is an exactly on topic conference paper and was cited on one (1) of the list of eleven papers.

[dos Santos Rosa et al, January 2010] was chosen because it is an exactly on topic journal paper that is written by a group of authors that published four exactly on topic papers - dos Santos Rosa et al [2009] (two papers) and dos Santos Rosa et al [2010] (two papers).

[Shao et al, January 2010] was chosen because it is an exactly on topic journal paper that was part of an important set of independent work published in 2010.

[Kokkinos et al, May 2010] was chosen because it is an exactly on topic conference paper that was part of an important set of independent work published in 2010.

[Georgakilas et al, August 2010] was chosen because it is an exactly on topic conference paper. Also, these authors are responsible for publishing three exactly on topic papers - Tzanakaki et al [2009] and Georgakilas et al [2010] (two papers).

[Patel et al, September 2010] was chosen because it is an exactly on topic conference paper that was cited on one (1) of the list of eleven papers. Also, this set of authors is part of a group of authors [Patel et al and Gao, et al] that collectively wrote six exactly on topic papers - Patel et al [2010] (three papers), Gao et al [2011] (two papers) and Gao et al [2012].

[Azodolmolky et al, October 2010] was chosen because it is an exactly on topic journal paper that was part of an important set of independent work published in 2010.

[Gao et al, 2012] was chosen because it is one of the latest journal parers that was published that is exactly on topic. Also, this set of authors formed the other part of the group of authors referred to above - Patel et al [2010] (three papers), Gao et al [2011] (two papers) and Gao et al [2012].

These papers are grouped by the general techniques used. Most of the researchers use the conventional RWA algorithm approach, but some also include the placement of traffic grooming equipment and/or regenerators while others include the shared risk link group (SRLG) approach.

1.6 The structure of the survey

The remainder of this survey is structured as follows:

Section 2 contains reviews of three (3) papers - Yang et al [2005], Patel et al [2010] and Gao et al [2012]. These papers are all concerned with the place-

ment of traffic grooming equipment and/or regenerators.

Section 3 contains reviews of six (6) papers - Zhai et al [2007], Markidis and Tzanakaki [2008], dos Santos Rosa [2010], Kokkinos et al [2010], Georgakilas et al [2010] and Azodolmolky et al [2010]. These papers are all concerned with conventional RWA algorithm approach.

Section 4 contains reviews of two (2) papers - Wang and Li [2007] and Shao et al [2010]. These two papers are both concerned with a method which uses the SRLG approach.

Section 5 contains the concluding comments and Section 6 the list of references.

1.7 Observations

It was observed that a significant number of the papers were written by a few authors. dos Santos Rosa et al wrote four (4) of the papers while a group of authors working with Gao and Patel wrote six (6) of the papers. Also, from their claims, it would appear that the authors were not aware of each others' work. It is thus, not surprising that sixteen (16) of the papers were published in 2009-2010, ten (10) alone in 2010.

2 METHODS WHICH USE TRAFFIC GROOMING AND REGENERATOR PLACEMENT

In this section, we review three papers describing research that attempts to solve the problem by methods which use traffic grooming equipment and/or regenerator. The methods are traffic grooming and/or regenerator placement under shared path protection, traffic grooming and/or regenerator placement with dedicated path protection and traffic grooming and/or regenerator placement with connection-level protection.

2.1 Traffic Grooming Under Shared Path Protection

The problem addressed
Yang et al [2005] address the problem of protecting impairment-aware WDM networks against failures by assigning wavelengths and optical-electrical-optical (O/E/O) modules along the working and protection paths.

Previous work referred to
The authors do not refer to any previous work that attempts to solve the problem.

The new algorithm
The researchers developed three approaches to solve the problem. An integer

linear program (ILP) approach that formulates the problem into a single IPL problem, and two heuristic approaches (LOH and TSH) that first find an initial solution by employing the divide-and-conquer and greedy principles. A directed graph is used to represent the network, with each vertex representing a network node and each edge representing a fiber link that has a fixed number of wavelengths. The objective is to minimize the number of O/E/O modules and wavelength links consumed by all the connection requests. In this approach k-shortest paths are chosen as candidates for the working path of each connection. Given the working path, another set of k-shortest paths is chosen as candidates for the protection path. A greedy wavelength and O/E/O assignment algorithm is then used to assign wavelengths and O/E/O modules along the working and protection paths.

The LOH (local optimization heuristic) approach is used to improve the initial solution, based on a reconfiguration evaluation procedure while the TSH (tabu-search heuristic), which the authors claim further optimize the solution, is based on a meta-heuristic for solving hard combinatorial optimization problems.

Experiments
Experiments were conducted on two networks; NET-A, a small-size network with 6 nodes and 9 bidirectional links, and NET-B, a network with 24 nodes and 43 bidirectional links. The ILP solution was tested only on NET-A, while the LOH and TSH were tested on both networks.

Results
The authors claim that their simulation results on NET-A revealed that the IPL solution becomes unacceptable when the number of wavelengths increased to four but both the LOH and TSH found the optimal solution in all the six cases in 60 seconds or less.

The cases are shown in the Table 1 below:

Case #	Wavelengths	Requests	Running Time (s)
1	2	3	509
2	2	4	2622
3	3	4	3287
4	3	5	4826
5	4	5	7200*
6	4	6	?

Table1: Running times (in seconds) for solving the IPL problem in NET-A. Survivable lightpath provisioning in WDM mesh networks under shared path protection and sign al quality constraints. Yang et al [2005], page 1564.

The authors also claim that, in all cases, the solutions obtained by TSH are better than those obtained by LOH. However, both TSH and LOH show signif-

icant improvement over the initial solution, and TSH has a 4 percent improvement over LOH in terms of the number of O/E/O modules used and 5 percent improvement over LOH in terms of the number of wavelength links used. In addition, they claim that based on their observations, TSH generates improvement move quickly than LOH and yields a better solution within the same amount of time.

Claims made
The authors claim that their results show that the tabu-search heuristic (TSH) outperforms the local optimization heuristic (LOH) and that both heuristic approaches can handle large-scale problems with a modest time complexity.

Cited by
This paper was cited by Zhai et al [2007], dos Santos Rosa et al [2010] and Kokkinos et al [2010].

2.2 Traffic Grooming with Dedicated Path Protection

The problem addressed
Patel et al [2010] address the problem of protection of impairment-aware traffic-grooming WDM networks against single failures by focusing on efficient placement of equipment.

Previous work referred to
The authors did not refer to any previous work that attempt to solve the problem.

The new algorithm and architecture
The authors developed a ROADM architecture that places traffic grooming equipment or a regenerator at each node. They also developed a heuristic algorithm that is based on an auxiliary graph that consists of physical links (physical network topology), auxiliary links (routes that satisfied the impairments constraints) and virtual links (established lightpaths with sufficient spare capacity for the request).

A new backup lightpath is established by finding the shortest path on the auxiliary graph that is a link disjoint from the working path. Regenerators are then placed at all intermediate nodes along the backup path. Also, if there is spare capacity, the algorithm establishes a separate working lightpath and a separate disjoint backup lightpath.

Experiments
Experiments were conducted, via simulations, on a 100-node meshed network topology in which each link is assumed to have a bidirectional fiber. Line rates of 10 Gbps, 40 Gbps and 100 Gbps with different optical reach were used in the simulations.

Results
The authors claim that their results show that the cost of the grooming-only approach is less than the cost of the regenerator-only approach and the cost of the combined traffic grooming and regenerator placement is always lower. They also claim that based on the results: at low load, the 10 Gbps network has the lowest cost; at moderate load, the 40 Gbps network has the lowest cost; and at high load, the 100 Gbps with reachability of 8 hops has the lowest cost.

Claims made
The authors claim that the efficient placement of traffic grooming and regenerators together for establishing survivable lightpaths reduces cost. They also claim that as the traffic load increases, the network can further be improved by increasing the line rate.

Cited by
This paper was cited by Gao et al [2012].

2.3 Traffic Grooming with Connection-level Protection

The problem addressed
The problem identified by Gao et al [2012] is protection of impairment-aware optical WDM networks against failures by focusing on improving utilization of network resources.

Previous work referred to
In 2010, a subset of the authors proposed a combined traffic grooming and regeneration placement approach to support all traffic demands with minimum cost. [Patel et al 2010].

Shortcomings of previous work identified
The authors claim that the solution of Patel et al [2010] may not be cost or resource efficient for cases in which the lightpath is not fully occupied.

The new architecture and algorithms
The authors developed a reconfigurable optical add-drop multiplexer (ROADM) node architecture. They state that this architecture has an all-optical wavelength switch fabric coupled with an electrical backbone, which together connects the various grooming and regenerator equipment.

The authors present two algorithms (a dedicated connection-level protection algorithm and a shared connection-level protection algorithm) that use auxiliary graphs that take into consideration the weight and residual capacity of each type of link. They note that, in each algorithm, the auxiliary graph is first generated and used to select the solution that generates the minimum network cost.

Experiments
The authors conducted experiments for both algorithms, on two simulated networks. A randomly generated 100-node network topology, whose average node degree is 4, and a 14-node NFS network with a node degree of 2.7.

Results
The authors claim that their results show that when comparing connection-level protection with lightpath-level protection, among other parameters, connection-level protection achieves lower cost, but has a higher signaling cost when a lightpath failure occurs.

Claims made
The authors claim that their stimulation results show that their approach outperforms a lightpath-level protection approach, in terms of network cost. They also claim to show that a network with higher line rate and longer optical reach can reduce the network cost, when the traffic load increases.

2.4 Section summary

A summary of the three papers in this section is shown in the table below.

Year	Title	Authors	Major contribution
2005	Survivable lightpath provisioning in WDM mesh networks under shared path protection and signal quality constraints	Yang, X., Shen L., and Ramamurthy, B.	Equipment placement and shared path protection
2010	Survivable impairment-aware traffic grooming with dedicated path protection dedicated path protection	Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Naito, T.	Equipment placement and dedicated path protection
2012	Survivable impairment-aware traffic grooming and regenerator placement with connection-level protection	Gao, C., Cankaya, H., Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Sekiya, M.	Equipment placement and connection-level protection

3 METHODS WHICH USE CONVENTIONAL RWA ALGORITHMS

In this section, we review six papers that attempt to solve the problem by methods which use conventional routing and wavelength algorithms (RWA).

3.1 RWA using lit or dark backup path protection

The problem addressed
Zhai et al [2007] address the problem of protecting impairment-aware DWDM

networks against single link failures by considering dedicated path protection schemes with lit and dark backup lightpaths.

Previous work referred to
Zhai et al [2007] refer to the work of Yang et al [2005].

Shortcomings of previous work identified
The authors claim that the solution of Yang et al [2005] did not consider fully transparent networks.

The new architecture
The researchers developed a model that considered circuit-switched all optical networks with no wavelength conversion. This model is based on two RWA algorithms Shortest Path with wavelength assignment (SP) and Highest Q-factor (HQ). In the HQ algorithm a shortest path algorithm is run on each wavelength to find a candidate path on a specific wavelength. The end-to-end Q-factor is then calculated and the path with the highest Q-factor is chosen for request.

For each traffic request, two new circuits (lightpaths) are tentatively established using one of the algorithms a primary circuit and a back circuit. In the backup circuit, the protected path is either lit or kept dark (unlit), resulting in two dedicated path protection schemes. With the lit back path protection scheme, SP runs a shortest path algorithm twice to compute two link-disjoint paths. Both paths are lit-up and the Quality of Transmission (QoT) blocking verification starts. With the dark backup path protection scheme, since only the primary path is lit, the QoT verification differs.

Experiments
Experiments were conducted to study the network performance of the two dedicated path protection schemes using a down scaled version of the NFS topology. In this network 14 nodes and 21 bidirectional links were used. The blocking probability and vulnerability ratio were used as the metric for performance comparison.

Results
The authors claim that their simulation results revealed that the HQ algorithm with lit backup paths performs better than the SP algorithm with dark backup paths. They also claim that HQ improves vulnerability ratio over SP by a large margin for the lit backup scheme than for the dark backup scheme.

For the dark backup scheme the authors claim that wavelength blocking dominates QoT blocking while in the lit backup scheme overall blocking probabilities were considerably higher; QoT blocking dominates wavelength blocking for the SP algorithm; and HP outperforms SP for blocking probability.

Claims made
The authors claim that their results show that HQ outperforms SP in terms of blocking probability and vulnerability ratio in a certain traffic load range in both dark and lit backup protection schemes.

Cited by
This paper was cited by dos Santos Rosa et al [2010], Shao et al [2010] and Kokkinos et al [2010].

3.2 RWA favouring resource sharing

The problem addressed
Markidis and Tzanakaki [2008] address the problem of protecting impairment-aware transparent optical WDM networks against failures by focusing on light-path provisioning taking into consideration the optical signal performance degradation triggered by the physical impairments.

Previous work referred to
The authors do not refer to any previous work that attempts to solve the problem.

The new algorithm
The researchers used two steps to solve the RWA problems. Routing is implemented based on Dijkstras algorithm, to compute a primary and a backup path. The Wavelength Assignment algorithms assign wavelength to primary and backup paths, favouring resource sharing between the current demand and the already established requests. After weights are assigned to the network links, Dijkstras algorithm is used to calculate the shortest path to find the primary path. If no suitable path (based on BER) is found, the connection is blocked. After selecting the primary path, the process is repeated to select the backup path, but the primary path is removed from the process. Random pick, first-fit or last-fit schemes are used to select a path from the list of candidate paths.

Experiments
Experiments were conducted and results generated, by simulations, on the Pan-European test network defined by COST 239 that comprises of 11 nodes and 26 bidirectional links each of capacity of 16 wavelengths. The behavior of last-fit, random-pick and first-fit for backup path were investigated. Physical layer constraints were considered separately.

Results
The authors claim that their results show that last-fit wavelength assignment scheme provides improved network performance of around 2 percent when compared to first-fit and significantly outperforms random-pick, since it can offer a blocking improvement of 12 percent for a wide range of traffic conditions. The authors also claim that network performance is significantly improved when the

impairment-aware routing scheme is compared to the impairment-unaware routing scheme, in terms of blocking probability.

Claims made
The authors claim that overall network performance can be improved when wavelength assignment algorithms, that are able to offer high spare capacity utilization, are implemented. In addition, they claim that the proposed IAR algorithm incorporated in the provisioning of protected lightpaths is able to provide guaranteed quality connections in a highly efficient manner.

Cited by
This paper was cited by Georgakilas et al [2010].

3.3 RWA using a shared protection scheme

The problem addressed
dos Santos Rosa et al [2010] address the problem of protecting impairment-aware WDM networks against failures by focusing on shared path protection schemes that take into consideration various physical impairments during path selection.

Previous work referred to
The authors refer to the work of Yang et al [2005], Zhai et al [2007] and Wang and Li [2007]

Shortcomings of previous work identified
The authors claim that Polarization Mode Dispersion (PMP), Amplifier Spontaneous Emission Noise (ASE) and cross-talk (CT) impairments were not considered in the previous work by other researchers.

The new algorithms
The researchers developed, what they claim to be, two novel algorithms using a shared protection scheme and impairments (PMP, ASE and CT) for the establishment of lightpaths. These algorithms are First-fit IASPP and Random-selection IASPP. First-fit takes a traffic request and executes a shortest path algorithm to find the primary path, in order of wavelength. Not considering the primary path, it then executes the same algorithm to search for a backup path. If a path is not available the request is blocked.

In the random-selection algorithm, there is no order and the layers are visited randomly. Random selection takes a request and executes the shortest path algorithm based on a random selection of a wavelength. It uses the same methodology for selecting the backup path, not considering the primary path. If a path is not available the request is blocked.

Experiments
Experiments were conducted using two network topologies: the NSF with 16

nodes and 25 bidirectional links and the USA with 24 nodes and 43 bidirectional links. The performance metric used is the blocking probability.

Results
The authors claim that in the NSF network topology, the results of FFIASPP and RSIASSP when compared to FFSSP and RSSSP (without impairment-aware) show: a significant increase in blocking probability is notices for impaired networks; the FFIASSP reduced the blocking probability from 0.32 to 0.2, while the RSIASPP reduced it from 0.3 to 0.17. In terms of vulnerability, the ratios vary very little.

In the USA network topology, the blocking probability increased in both aware and unaware algorithms. In terms of vulnerability, the figures were lower than those obtained in the NSF topology.

Claims made
The authors claim that results show that this approach decreases blocking, yet maintains a similar level of vulnerability.

3.4 RWA using a multicost approach

The problem addressed
Kokkinos et al [2010] address the problem of protecting impairment-aware WDM optical networks against failures by selecting the primary path and the backup path, jointly.

Previous work referred to
The authors refer to the work of Yang et al [2005], Zhai et al [2007] and Azodolmolky et al [2009].

Shortcomings of previous work identified
The authors claim that in the work of Yang et al [2005] only considered two linear constraints (PMD and ASE) and ignored all the other physical constraints. They also claim that in the work of Zhai et al [2007], keeping the backup path lit worsen the impairments for other lightpaths and keeping the backup path dark can lead to increased traffic restoration time. They further claim that the work of Azodolmolky et al [2009] was limited to transparent all optical networks and only considered dedicated path protection for offline demands.

The new idea and algorithm
The authors developed a multicost approach that they claim is significantly more powerful than single cost routing. A vector of cost parameters, which includes the utilization of wavelengths, is assign to each link. These cost parameters are used to calculate the cost vector of a path. In this multicost approach more than one path is calculated between two nodes and, as such, minimization and maximization can be used to arrive at the best path. This approach consists

of two phases. The first phase uses an algorithm that is a generalization of the Dijkstras algorithm which obtains a set of candidate non-dominated lightpaths for a given connection request. In the second phase, a primary lightpath is selected to serve the connection request while a second lightpath, from the same set is selected as the backup path.

Experiments
The authors conducted simulation experiments considering an all-optical network where connections arrived dynamically and have to be served as they come. The blocking probability of several multicost based algorithms as a function of the number of available wavelengths, performing 1+1 and 1:1 protection were measured.

Results
The authors claim that the results show that in case of 1+1 protection, the sumQ and bestQ-bestQ policies result in similar blocking probability and in the case of 1:1 protection, the differences between the different protection policies are minimized. They also claim that there is a level of trade off between the level of protection (1+1, 1:1 and no protection). In addition, the authors claim that the usage of the worse case interference assumption for the selection of backup lightpath reduces the blocking probability.

Claims made
The authors claim that, based on their experimental observations, the joint selection of the primary and backup lightpaths is generally more preferable than selecting them separately. They also claim to show that the selection of backup lightpath, based on the worse case interference assumption can be quite beneficial for the survivability of the backup paths, when the network is heavily loaded. In addition, they claim that the problem is NP-complete.

3.5 RWA using a modular approach

The problem addressed
Georgakilas et al [2010] address the problem of protecting impairment-aware WDM networks against failures by focusing on performance evaluation in impairment-aware routing under single and double link failures in identifying the primary and backup paths.

Previous work referred to
The authors refer to the work of Markadis and Tzanakaki [2008].

Shortcomings of previous work identified
The authors claim that the work of Markadis and Tzanakaki [2008] did not take into consideration double-link failures.

The new idea and algorithm
The authors developed a modular approach that divides the problem into several modules. The RWA problem is solved in two steps: routing and wavelength assignment (RWA) for the primary path and RWA for the backup path. Both steps are implemented using Dijkstras algorithm. The primary path for each request is computed by the impairment-aware RWA scheme and uses a first-fit algorithm based on the quality of the paths (a predefined BER threshold) for wavelength assignment. The backup path is computed using IA and minimum-hop routing and uses the weighted last-fit algorithm for wavelength assignment (also based on the BER threshold)

Experiments
Four Experiments, based on simulations, were evaluated using two network topologies: the COST 239 topology and the NSFNET topology. The scenarios are shown in the table below:

Scenario	Backup Path Routing	Reinforced Sharing
Sc1	IAR	Yes
Sc2	IAR	No
Sc3	min-hop	Yes
Sc4	min-hop	No

Table 1: Evaluation Scenarios Definitions, Performance evaluation of impairment-aware routing under single- and double-link failures. Georgakilas et al [2010], page 637.

Results
The authors claim that they observed that when IAR was applied for the backup path computation, the total blocking probability for the COST 239 topology was much lower compared with the min-hop; for all load conditions, the blocking probability is reduced by more than 50 percent. In the NSFNET, the IAR also demonstrated reduction in blocking probability. They also claimed that when reinforced sharing is applied there is better resource utilization.

Claims made
The authors claim that when the quality of the formed paths is taking into account in the process of routing, the physical performance of the selected paths is shown to be better, compared with the traditional routing schemes that considers only bandwidth availability. They also claim that the impairment-aware routing scheme provides better performance under single- and dual-links failures. In addition, they claim that the consideration of impairments in the routing algorithm for both the primary and backup paths provides a reduced network blocking probability.

3.6 RWA using a pre-processing module to order traffic demands

The problem addressed
Azodolmolky et al [2010] address the problem of protecting impairment-aware WDM networks against failures by focusing on offline physical layer impairment aware routing with dedicated path protection consideration.

Previous work referred to
The authors do not refer to any previous work that attempts to solve the problem.

The new algorithms
In this performance evaluation, the authors developed three algorithms. They enhanced two existing IA-RWA algorithms (the RS-RWA algorithm and an ILP-based RWA algorithm) that did not considered dedicated path protection. The two offline IA-RWA algorithms were extended to consider dedicated path protection. The performances of these two algorithms were compared with that of a new IA-RWA algorithm (the Rahyab algorithm). The new algorithm uses a demand pre-processing module to order the traffic demands and a process to select a lightpath form the candidate lightpath list. Traffic demands can be protected or unprotected.

Experiments
Experiments were conducted based on simulations that used the Deutsche Telekom National Network (DTNet) which 14 nodes and 23 bidirectional links, with an average node degree of 3.29.

Results
The authors claim that their results show that the performance of the ILP-RWA-LU (1 SP) is better than the original ILP-RWA algorithms (both 1 SP and 2 SP). They also claim that their results indicate that increasing the number of candidate shortest paths also increases the blocking rate of ILP-RWA and ILP-RWA-LU algorithms.

Claims made
The authors claim that their enhancements to the RS-RWA heuristic (that is, RS-RWA-Q) reduced the blocking rate of demands by an average of 35 percent from different loads compared to the original scheme (RS-RWA); the performance of ILP-RWA-LU (1 sp) formulation (enhanced IRL-RWA) is also improved by 71 percent; and the Rehab algorithm performs better than the two algorithms with respect to the blocking rate performance metric.

3.7 Section summary

A summary of the six papers in this section is shown in the table below.

Year	Title	Authors	Major contribution
2007	Performance of dedicated path protection in transmission-impaired DWDM networks	Zhai, Y., Pointurier, Y., Subramanian, S. and Brandt-Pearce, M.	RWA and dedicated path protection
2008	Routing and Wavelength assignment in survivable WDM networks under physical layer constraints	Markidis, G. and Tzanakaki, A.	RWA and lightpath provisioning
2010 Jan	Path protection WDM networks with impaired-transmission	dos Santos Rosa, S., Drummond, A. and da Donseka, N.	RWA and shared path protection
2010 May	Path protection in WDM networks with quality of transmission limitations	Kokkinos, P., Manousakis, K. and Varvarigos, E.	RWA and joint selection of primary and backup paths
2010 Aug	Performance evaluation of impaired-aware routing under single- and double-link failures	Georgakilas, K., Katrinis, K., Tzanakaki, A. and Madsen, O.	RWA and single and double-link failures
2010 Oct	A novel offline physical layer impairments aware RWA algorithm with dedicated path protection considerations	Azodolmolky, S., Klinkowski, M., Pointurier, Y., Angelou, M., Careglio, D., Sol-Pareta, J. and Tomkos, I.	RWA and dedicated path protection

4 METHODS WHICH USE SRLG APPROACH

In this section, we review two papers that attempt to solve the problem by methods which use shared risk link group (SRLG). The methods are impairment-aware optimal routing considering SRLG and performance enhancement for SRLG failures.

4.1 Impairment-aware optimal diverse routing

The problem addressed
Wang and Li [2007] address the problem of protecting impairment-aware WDM networks against failures by selecting reliable lightpaths to be used as primary and backup paths.

Previous work referred to
The authors refer to the work of Zang et al [2002]

Shortcomings of previous work identified
The authors claim that in the work of Zang et al [2002], the searching process is not complete and the solution is not optimal, in terms of the total cost of the two SRLG-disjoint paths, for Separate Path Selection (SPS), Joint Path Selection (JPS) and Low-cost Pair of SRLG-Disjoint (LPSD). They also claim that the Modified Weight (MW) gives optimal solution only when the two paths are required to be link or node disjoint but not SRLG-disjoint. More so, they further claim that the algorithm can only be applied in a static traffic environment.

The new algorithms
The authors developed, what they claim to be, two novel algorithms to calculate an optimal path pair for a given connection requirement from a source node to a destination node (s-d pair). The optimal path has two definitions and thus, two versions of the problem are defined (IAOPP-I and IAOPP-II). The first algorithm has two versions (MUCOPPON-I and MUCOPPON-II) which solve the IAOPP-I and IAOPP-II problems respectively. In MUCOPPON, the cost of a path pair has two definitions. In MUCOPPON-I, it is defined as the sum of primary costs of the two paths while in MUCOPPON-II, it is defined as the lower primary cost of the two paths. The other algorithm (DEPPON) can be used to solve the IAOPP-II problem only. It tries to find the optimal path pair in a path-by-path manner.

Experiments
Experiments were conducted to study the MUCOPPON and DEPPON algorithms in two network topologies: the Pan-European test network COST 239 with 11 nodes and 26 links, and the ItalianNet with 21 nodes and 36 links. The Success Ratio and average primary cost were used as the metric for performance comparison. For comparison, another algorithm, the MSPS algorithm was used.

Results
The results are shown in Table 1 and Table 2 on the following page.

Claims made
The authors claim that their simulation results prove the feasibility and good performance of MUCCOPON and DEPPON to address the special issues of routing lightpaths in wavelength-routed all-optical networks.

Cited by
This paper was cited by dos Santos Rosa et al [2010].

Table 1 and Table 2

$COST239, N_W = 32, D_{Max} = 2,500(B = 40, D_{PMD} = 0.05), H_{max} = 10, averageload = 100Erlang.$

		MUCOPPON-I	MUCOPPON-II	DEPPON	MSPS
SR		0.998	0.998	0.998	0.374
AvgPriCost	Working path	100.101	99.193	99.193	65.578
	Path pair	285.385	325.635	286.632	203.216

Table1: Impairment aware optimal diverse routing for survivable optical networks. Wang and Li [2007], page 149.

$ItalianNet, N_W = 32, D_{Max} = 2,500(B = 40, D_{PDM} = 0.05), H_{max} = 10, averageload = 100Erlang.$

		MUCOPPON-I	MUCOPPON-II	DEPPON	MSPS
SR		0.825	0.825	0.825	0.405
AvgPriCost	Working path	225.669	219.777	219.777	136.284
	Path pair	620.589	659.981	636.908	412.58

Table2: Impairment aware optimal diverse routing for survivable optical networks. Wang and Li [2007], page 149.

4.2 Performance enhancement for SRLG failures

The problem addressed
Shao et al [2012] address the problem of protecting impairment-aware WDM networks against SRLG failures by selecting working and backup paths with SRLG-disjoint constraints.

Previous work referred to
The authors refer to the work of Zhai et al [2007]

Shortcomings of previous work identified
The authors claim that in the work of Zhai et al [2007] connections with a longer working path or backup path will be rejected.

The new idea
The new idea considers two policies: Policy I and Policy II. Policy I is used to satisfy impairment constraints. It computes the two least impairment paths. The first path is computed the working path and then another path is compute for the backup path. Policy II is based on capacity efficiency. It tries to benefit from both the shortest path and the least impaired path by choosing them intelligently.

Experiments
The authors conducted two experiments, based on simulations, one using a 14-node network topology and the other using a 28-node network topology. They

compare the Policy I and Policy II based physical impairment-aware shared-path protection (SPP) with impairment-unaware SPP that does not consider physical impairment.

Results
The authors claim that the results show that the two impairment-aware methods significantly outperform impairment-unaware SSP with the presence of physical impairment constraints. Also, they claim that the results show that generally, the impairment-aware SPP based on Policy II outperforms that based on Policy I in terms of blocking probability.

Claims made
The authors claim that when compared with impairment-unaware SRLG failure protection, impairment-aware performs much better in terms of blocking probability especially with strong physical impairment constraints. They also claim that impairment-aware SRLG failure protection can significantly reduce physical-layer blocking probability, and the algorithm based on Policy II achieves a good balance between capacity efficiency and physical impairment requirements. In addition they claim that the problem is NP-complete.

4.3 Section summary

A summary of the papers in this section is shown in the table below.

Year	Title	Authors	Major contribution
2007	Impairment aware optimal diverse routing for survivable optical networks	Wang, S., and Li, L.	Consideration for protection and SRLG failures
2010	Performance enhancement for impairment-aware SRLG failure protection in wavelength-routed optical networks	Shao, X., Yeo, K., Zhou, L., Wang, Y., and Bai, Y.	Consideration for protection and SRLG failures

5 CONCLUDING COMMENTS

Twenty nine (29) papers related to the topic of the survey were identified and eleven of them were reviewed in detail. In doing so, the following observations were made:

1. There appears to be a limited set of researchers doing work in this area, as four (4) of the papers were written by members of one research group. This group consists of three members (dos Santos Rosa, S., Drummond, A., and da Fonseca, N.), all from the Institute of Computing, University of Campinas, Campinas, Brazil. Two of the papers were published in 2009 - dos Santos Rosa et al [2009] and another two in 2010 - dos Santos Rosa et al [2010].

Another six (6) of the papers were written by an extended group of researchers. This extended group consists of nine researchers (Gao, C., Cankaya, H., Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., Naito, T., and Sekiya, M.). Three of the papers were published in 2010 - Patel et al [2010], two more in 2011 - Gao et al [2011] and yet another in 2012 - Gao et al [2012].

2. The authors were probably not aware of each other work, as many of the them claimed to be the first to provide a particular methodology. This is probably a result of the fact that they were working at the same time, and ten (10) of the papers were published in 2010.

To provide a better understanding of the nature of the research in this area, the table below list the eleven most important papers, which papers were referred to (cites) and who cites the original paper (cited by).

Paper	Cites	Cited by
Yang et al 2005		Zhai et al 2007 dos Santos Rosa et al 2010 Kokkinos et al 2010
Zhai et al 2007	Yang et al 2005	dos Santos Rosa et al 2010 Shao et al 2010 Kokkinos et al 2010
Wang and Li 2007	Zang et al 2002	dos Santos Rosa et al 2010
Markidis and Tanakaki 2008		Georgakilas et al 2010
dos Santos Rosa et al 2010	Yang et al 2005 Zhai et al 2007 Wang and Li 2007	
Shao et al 2010	Zhai et al 2007	
Kokkinos et al 2010	Yang et al 2005 Zhai et al 2007 Azodolmolky et al 2009	
Georgakilas et al 2010	Markidis and Tanakaki 2008	
Patel et al 2010		Gao et al 2012
Azodolmolky et al 2010		
Gao et al 2012	Patel et al 2010	

The researchers mentioned the following future work:

a) Yang et al [April 2005] state that the more generic shared risk link group (SRLG)-diverse protection can be incorporated into the problem and can be handled by enhancing their solution approaches.

b) Zhai et al [June 2007] state that they intend to develop less time-consuming QoT-aware algorithm with blocking probability and vulnerability ratio performance comparable to those of the Highest Q factor algorithm. They also state

that more complicated protection schemes (such as shared protection) and failure types (such as Shared Risk Link Group and multi-link failures) will need to be investigated.

c) Shao et al [January 2010] state that future work includes studying the problem of how to support quality of Protection (QoP) classes of surviving SRLG failures and Quality of Transmission (QoT) by differentiated QoP and QoT provisioning.

d) Azodolmolky et al [October 2010] state that proper integration of IA-RWA algorithms with control plane and its impact on control plane operation are among their ongoing activities.

References

[1] Azodolmolky, S., Klinkowski, M., Pointurier, Y., Angelou, M., Careglio, D., Sol-Pareta, J., and Tomkos, I. 2010. A novel offline physical layer impairments aware RWA algorithm with dedicated path protection consideration. *Journal of Lightwave Technology, 28, 20, 3029-3040.*

[2] Azodolmolky, S., Pointurier, Y., Angelou, M., Sole Pareta, J., and Tomkos, I. 2009. An offline impairment aware RWA algorithm with dedicated path protection consideration. *Optical Fiber Communication - incudes post deadline papers, 2009. OFC 2009. Conference, 1-3.*

[3] Bao, N.-H., Li, L.-M., Luo, H.-B., Yu, H.-F., and Zhang, Z.-Z. 2012. Impairment aware sharing constraint relaxed path protection in translucent optical networks. *Opt. Eng. 51(4), 045002 Apr 06, 2012. doi:10.1117/1.OE.51.4.045002.*

[4] dos Santos Rosa, S., Drummond, A., and da Fonseca, N. 2009. Lightpath establishment in WDM networks with best effort shared path protection in impaired-transmissions. *Communications, 2009. ICC '09. IEEE International Conference, 1-6.*

[5] dos Santos Rosa, S., Drummond, A., and da Fonseca, N. 2009. Performance of best effort shared path protection mechanism under physical impairments in WDM networks. *Optical Network Design and Modeling, 2009. ONDM, International Conference, 1-6.*

[6] dos Santos Rosa, S., Drummond, A., and da Fonseca, N. 2010. Path protection WDM networks with impaired-transmission. *Photonic Network Communications, 19, 2 , 212-222.*

[7] dos Santos Rosa, S., Drummond, A., and da Fonseca, N. 2010. Shared path protection with differentiated reliability in transmission impaired WDM networks. *Communications (ICC), 2010 IEEE International Conference, 1-6.*

[8] Gao, C., Cankaya, H., Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Sekiya, M. 2011. Survivable impairment-aware traffic grooming and regenerator placement with dedicated connection level protection. *Communications (ICC), 2011 IEEE International Conference, 1-5.*

[9] Gao, C., Cankaya, H., Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Sekiya, M. 2011. Survivable impairment-aware traffic grooming and regenerator placement with shared connection-level protection. *Transparent Optical Networks (ICTON), 2011 13th International Conference, 1-4.*

[10] Gao, C., Cankaya, H., Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Sekiya, M. 2012. Survivable impairment-aware traffic grooming and regenerator placement with connection-level protection. *Optical Communications and Networking, IEEE OSA Journal. 4, 3, 259-270.*

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[14] Kokkinos, P., Manousakis, K., and Varvarigos, E. 2010. Path protection in WDM networks with quality of transmission limitations. *Communications (ICC), 2010 IEEE International Conference, 1-5.*

[15] Lee, Y., and Mukherjee, B. 2004. Traffic engineering in next-generation optical networks. *Communications Surveys and Tutorials, IEEE 6, 3, 16-33.*

[16] Markidis, G., and Tzanakaki, A. 2008. Routing and wavelength assignment algorithms in survivable WDM networks under physical layer constraints. *Broadband Communications, Networks and Systems, 2008. BROADNETS 2008. 5th International Conference, 191-196.*

[17] Patel, A., Gao, C., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Naito, T. 2010. Traffic grooming and regenerator placement in impairment-aware optical WDM networks. *Optical Network Design and Modeling (ONDM), 2010 14th Conference, 1-6.*

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[22] Shao, X., Zhou, L., Chai, T. Y., Saradhi, C. V., and Wang, Y. 2008. Reducing vulnerability of shared-path protection subject to double-link failures in WDM mesh networks. *Photonic Network Communications 15, 2, 171-181*

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Annotations

Yang, X., Shen, L., and Ramamurthy, B. 2005. Survivable lightpath provisioning in WDM mesh networks under shared path protection and signal quality constraints. *Lightwave Technology, Journal of April 2005. 23, 4, 1556-1567.*

The problem which the researcher/authors addressed
The authors address the problem of protecting impairment-aware WDM networks against failures by assigning wavelengths and optical-electrical-optical (O/E/O) modules along the working and protection paths.

Previous work by other authors referred to by the authors
The authors do not refer to any previous work that attempts to solve the problem.

The new idea, algorithm, architecture, protocol, etc.
The researchers developed three approaches to solve the problem. An integer linear program (ILP) approach that formulates the problem into a single IPL problem, and two heuristic solutions approaches (LOH and TSH) that first find an initial solution by employing the divide-and-conquer and greedy principles. A directed graph is used to represent the network, with each vertex representing a network node and each edge representing a fiber link that has a fixed number of wavelengths. The objective is to minimize the number of O/E/O modules and wavelength links consumed by all the connection requests. In this approach k-shortest paths are chosen as candidates for the working path of each connection. Given the working path, another set of k-shortest paths is chosen as candidates for the protection path. A greedy wavelength and O/E/O assignment algorithm is then used to assign wavelengths and O/E/O modules along the working and protection paths.

The LOH (local optimization heuristic) approach is used to improve the initial solution, based on a reconfiguration evaluation procedure while the TSH (tabu-search heuristic), which the authors claim further optimize the solution, is based on a meta-heuristic for solving hard combinatorial optimization problems.

Experiments and/or analyses conducted
Experiments were conducted on two networks; NET-A, a small-size network with 6 nodes and 9 bidirectional links, and NET-B, a network with 24 nodes and 43 bidirectional links. The ILP solution was tested only on NET-A, while the LOH and TSH were tested on both networks.

Results that the authors claimed to have achieved
The authors claim that their simulation results on NET-A revealed that the IPL solution becomes unacceptable when the number of wavelengths increased to four but both the LOH and TSH found the optimal solution in all the six cases in 60 seconds or less.

The cases are shown in the Table 1 below:

Case #	Wavelengths	Requests	Running Time (s)
1	2	3	509
2	2	4	2622
3	3	4	3287
4	3	5	4826
5	4	5	7200*
6	4	6	?

Table1: Running times (in seconds) for solving the IPL problem in NET-A. Survivable lightpath provisioning in WDM mesh networks under shared path protection and sign al quality constraints [2005]. Yang et al, page 1564.

The authors also claim that, in all cases, the solutions obtained by TSH are better than those obtained by LOH. However, both TSH and LOH show significant improvement over the initial solution, and TSH has a 4 percent improvement over LOH in terms of the number of O/E/O modules used and 5 percent improvement over LOH in terms of the number of wavelength links used. In addition, they claim that based on their observations, TSH generates improvement move quickly than LOH and yields a better solution within the same amount of time.

Claims made by the authors
The authors claim that their results show that the tabu-search

heuristic (TSH) outperforms the local optimization heuristic (LOH) and that both heuristic approaches can handle large-scale problems with a modest time complexity.

Zhai, Y., Pointurier, Y., Subramanian, S., and Brandt-Pearce, M. 2007. Performance of dedicated path protection in transmission-impaired DWDM networks. *In: Proceedings of IEEE International conference on communication, 2342-2347.*

The problem which the researcher/authors addressed
The authors address the problem of protecting impairment-aware DWDM networks against single link failures by considering dedicated path protection schemes with lit and dark backup lightpaths.

Previous work by other authors referred to by the authors
[Yang et al 2005]

Shortcomings of previous work
The authors claim that the solution of Yang et al [2005] did not consider fully transparent networks.

The new idea, algorithm, architecture, protocol, etc.
The researchers developed a model that considered circuit-switched all optical networks with no wavelength conversion. This model is based on two RWA algorithms Shortest Path with wavelength assignment (SP) and Highest Q-factor (HQ). In the HQ algorithm a shortest path algorithm is run on each wavelength to find a candidate path on a specific wavelength. The end-to-end Q-factor is then calculated and the path with the highest Q-factor is chosen for request.

For each traffic request, two new circuits (lightpaths) are tentatively established using one of the algorithms a primary circuit and a back circuit. In the backup circuit, the protected path is either lit or kept dark (unlit), resulting in two dedicated path protection schemes. With the lit back path protection scheme, SP runs a shortest path algorithm twice to compute two link-disjoint paths. Both paths are lit-up and the Quality of Transmission (QoT) blocking

verification starts. With the dark backup path protection scheme, since only the primary path is lit, the QoT verification differs.

Experiments and/or analyses conducted
Experiments were conducted to study the network performance of the two dedicated path protection schemes using a down scaled version of the NFS topology. In this network 14 nodes and 21 bidirectional links were used. The blocking probability and vulnerability ratio were used as the metric for performance comparison.

Results that the authors claimed to have achieved
The authors claim that their simulation results revealed that the HQ algorithm with lit backup paths performs better than the SP algorithm with dark backup paths. They also claim that HQ improves vulnerability ratio over SP by a large margin for the lit backup scheme than for the dark backup scheme.

For the dark backup scheme the authors claim that wavelength blocking dominates QoT blocking while in the lit backup scheme overall blocking probabilities were considerably higher; QoT blocking dominates wavelength blocking for the SP algorithm; and HP outperforms SP for blocking probability

Claims made by the authors
The authors claim that their results show that HQ outperforms SP in terms of blocking probability and vulnerability ratio in a certain traffic load range in both dark and lit backup protection schemes.

Wang, S., and Li, L. 2007. Impairment aware optimal diverse routing for survivable optical networks. *Photonic Network Communications April 2007, 13, 2, 139-154.*

The problem which the researcher/authors addressed
The authors address the problem of protecting impairment-aware WDM networks against failures by selecting reliable lightpaths to be used as primary and backup paths.

Previous work by other authors referred to by the authors

[Zang et al 2002]

Shortcomings of previous work
The authors claim that in the work of Zang et al [2002], the searching process is not complete and the solution is not optimal, in terms of the total cost of the two SRLG-disjoint paths, for Separate Path Selection (SPS), Joint Path Selection (JPS) and Low-cost Pair of SRLG-Disjoint (LPSD). They also claim that the Modified Weight (MW) gives optimal solution only when the two paths are required to be link or node disjoint but not SRLG-disjoint. More so, they further claim that the algorithm can only apply in static traffic environment.

The new idea, algorithm, architecture, protocol, etc.
The authors developed, what they claim to be, two novel algorithms to calculate optimal path pair for a given connection requirement from a source node to a destination node (s-d pair). The optimal path has two definitions and thus, two versions of the problem are defined (IAOPP-I and IAOPP-II). The first algorithm has two versions (MUCOPPON-I and MUCOPPON-II) which solve the IAOPP-I and IAOPP-II problems respectively. In MUCOPPON, the cost of a path pair has two definitions. In MUCOPPON-I, it is defined as the sum of primary costs of the two paths while in MUCOPPON-II, it is defined as the lower primary cost of the two paths. The other algorithm (DEPPON) can be used to solve the IAOPP-II problem only. It tries to find the optimal path pair in a path-by-path manner.

Experiments and/or analyses conducted
Experiments were conducted to study the MUCOPPON and DEPPON algorithms in two network topologies: the Pan-European test network COST 239 with 11 nodes and 26 links, and the ItalianNet with 21 nodes and 36 links. The Success Ratio and average primary cost were used as the metric for performance comparison. For comparison, another algorithm, the MSPS algorithm was used.

Results that the authors claimed to have achieved
The results are shown in Table 1 and Table 2 below:

$COST239, N_W = 32, D_{Max} = 2,500(B = 40, D_{PMD} = 0.05), H_{max} = 10, averageload = 100Erlang.$

		MUCOPPON-I	MUCOPPON-II	DEPPON	MSPS
SR		0.998	0.998	0.998	0.374
AvgPriCost	Working path	100.101	99.193	99.193	65.578
	Path pair	285.385	325.635	286.632	203.216

Table1: Impairment aware optimal diverse routing for survivable optical networks [2007] Wang, S and Li, L, page 149.

$ItalianNet, N_W = 32, D_{Max} = 2,500(B = 40, D_{PDM} = 0.05), H_{max} = 10, averageload = 100Erlang.$

		MUCOPPON-I	MUCOPPON-II	DEPPON	MSPS
SR		0.825	0.825	0.825	0.405
AvgPriCost	Working path	225.669	219.777	219.777	136.284
	Path pair	620.589	659.981	636.908	412.58

Table2: Impairment aware optimal diverse routing for survivable optical networks [2007] Wang, S and Li, L, page 149.

Claims made by the authors
The authors claim that their simulation results prove the feasibility and good performance of MUCCOPON and DEPPON to address the special issues of routing lightpaths in wavelength-routed all-optical networks.

Markidis, G., and Tzanakaki, A. 2008. Routing and wavelength assignment algorithms in survivable WDM networks under physical layer constraints. *Broadband Communications, Networks and Systems, 2008. BROADNETS 2008. 5th International Conference, 191-196.*

The problem which the researcher/authors addressed
The authors address the problem of protecting impairment-aware transparent optical WDM networks against failures by focusing on lightpath provisioning taking into consideration the optical signal performance degradation triggered by the physical impairments.

Previous work by other authors referred to by the authors
The authors do not refer to any previous work that attempts to

solve the problem.

The new idea, algorithm, architecture, protocol, etc.
The researchers used two steps to solve the RWA problems. Routing is implemented based on Dijkstras algorithm, to compute a primary and a backup path. The Wavelength Assignment algorithms assign wavelength to primary and backup paths, favouring resource sharing between the current demand and the already established requests. After weights are assigned to the network links, Dijkstras algorithm is used to calculate the shortest path to find the primary path. If no suitable path (based on BER) is found, the connection is blocked. After selecting the primary path, the process is repeated to select the backup path, but the primary path is removed from the process. Random pick, first-fit or last-fit schemes are used to select a path from the list of candidate paths.

Experiments and/or analyses conducted
Experiments were conducted and results generated, by simulations, on the Pan-European test network defined by COST 239 that comprises of 11 nodes and 26 bidirectional links each of capacity of 16 wavelengths. The behavior of last-fit, random-pick and first-fit for backup path were investigated. Physical layer constraints were considered separately.

Results that the authors claimed to have achieved
The authors claim that their results show that last-fit wavelength assignment scheme provides improved network performance of around 2 percent when compared to first-fit and significantly outperforms random-pick, since it can offer a blocking improvement of 12 percent for a wide range of traffic conditions. The authors also claim that network performance is significantly improved when the impairment-aware routing scheme is compared to the impairment-unaware routing scheme, in terms of blocking probability.

Claims made by the authors
The authors claim that overall network performance can be improved when wavelength assignment algorithms, that are able to offer high spare capacity utilization, are implemented. In addition, they claim that the proposed IAR algorithm incorporated in the

provisioning of protected lightpaths is able to provide guaranteed quality connections in a highly efficient manner.

dos Santos Rosa, S., Drummond, A., and da Fonseca, N. 2010. Path protection WDM networks with impaired-transmission. *Photonic Network Communications, 19, 2 , 212-222.*

The problem which the researcher/authors addressed
The researchers address the problem of protecting impairment-aware WDM networks against failures by focusing on shared path protection schemes that take into consideration various physical impairments during path selection.

Previous work by other authors referred to by the authors
[Yang et al 2005] [Zhai et al 2007] [Wang and Li 2007]

Shortcomings of previous work
The authors claim that Polarization Mode Dispersion (PMP), Amplifier Spontaneous Emission Noise (ASE) and cross-talk (CT) impairments were not considered in the previous work by other researchers.

The new idea, algorithm, architecture, protocol, etc.
The researchers developed, what they claim to be, two novel algorithms using a shared protection scheme and impairments (PMP, ASE and CT) for the establishment of lightpaths. These algorithms are First-fit IASPP and Random-selection IASPP. First-fit takes a traffic request and executes a shortest path algorithm to find the primary path, in order of wavelength. Not considering the primary path, it then executes the same algorithm to search for a backup path. If a path is not available the request is blocked.

In the random-selection algorithm, there is no order and the layers are visited randomly. Random selection takes a request and executes the shortest path algorithm based on a random selection of a wavelength. It uses the same methodology for selecting the backup path, not considering the primary path. If a path is not available the request is blocked.

Experiments and/or analyses conducted
Experiments were conducted using two network topologies: the NSF with 16 nodes and 25 bidirectional links and the USA with 24 nodes and 43 bidirectional links. The performance metric used is the blocking probability.

Results that the authors claimed to have achieved
The authors claim that in the NSF network topology, the results of FFIASPP and RSIASSP when compared to FFSSP and RSSSP (without impairment-aware) show: a significant increase in blocking probability is notices for impaired networks; the FFIASSP reduced the blocking probability from 0.32 to 0.2, while the RSIASPP reduced it from 0.3 to 0.17. In terms of vulnerability, the ratios vary very little.

In the USA network topology, the blocking probability increased in both aware and unaware algorithms. In terms of vulnerability, the figures were lower than those obtained in the NSF topology.

Claims made by the authors
The authors claim that results show that this approach decreases blocking, yet maintains similar level of vulnerability.

Shao, X., Cheng, X., Yeo, Y. K., Zhou, L., Wang, Y., and Bai, Y. 2010. Performance enhancement for impairment-aware SRLG failure protection in wavelength-routed optical networks. *Photonic Network Communications 20, 1, 1-9.*

The problem which the researcher/authors addressed
The researchers address the problem of protecting impairment-aware WDM networks against SRLG failures by selecting working and backup paths with SRLG-disjoint constraints.

Previous work by other authors referred to by the authors
[Zhai et al 2007]

Shortcomings of previous work

The authors claim that in the work of Zhai et al [2007] connections with a longer working path or backup path will be rejected.

The new idea, algorithm, architecture, protocol, etc.
The new idea considers two policies: Policy I and Policy II. Policy I is used to satisfy impairment constraints. It computes the two least impairment paths. The first path is computed the working path and then another path is compute for the backup path. Policy II is based on capacity efficiency. It tries to benefit from both the shortest path and the least impaired path by choosing them intelligently.

Experiments and/or analyses conducted
The authors conducted two experiments (simulations), one using a 14-node topology and the other using a 28-node topology. They compare the Policy I and Policy II based physical impairment- aware shared-path protection (SPP) with impairment-unaware SPP that does not consider physical impairment.

Results that the authors claimed to have achieved
The authors claim that the results show that the two impairment-aware methods significantly outperform impairment-unaware SSP with the presence of physical impairment constraints. Also, they claim that the results show that generally, the impairment-aware SPP based on Policy II outperforms that based on Policy I in terms of blocking probability.

Claims made by the authors
The authors claim that when compared with impairment-unaware SRLG failure protection, impairment-aware performs much better in terms of blocking probability especially with strong physical impairment constraints. They also claim that impairment-aware SRLG failure protection can significantly reduce physical-layer blocking probability, and the algorithm based on Policy II achieves a good balance between capacity efficiency and physical impairment requirements. In addition they claim that the problem is NP-complete.

Kokkinos, P., Manousakis, K., and Varvarigos, E. 2010. Path protection in WDM networks with quality of transmission lim-

itations. *Communications (ICC), 2010 IEEE International Conference, 1-5.*

The problem which the researcher/authors addressed
The researchers address the problem of protecting impairment-aware WDM optical networks against failures by selecting the primary path and the backup path, jointly.

Previous work by other authors referred to by the authors
[Yang et al 2005] [Zhai et al 2007] [Azodolmolky et al 2009]

Shortcomings of previous work
The authors claim that in the work of Yang et al [2005] only considered two linear constraints (PMD and ASE) and ignored all the other physical constraints. They also claim that in the work of Zhai et al [2007], keeping the backup path lit worsen the impairments for other lightpaths and keeping the backup path dark can lead to increased traffic restoration time. They further claim that the work of Azodolmolky et al [2009] was limited to transparent all optical networks and only considered dedicated path protection for offline demands.

The new idea, algorithm, architecture, protocol, etc.
The authors developed a multicost approach that they claim is significantly more powerful than single cost routing. A vector of cost parameters, which includes the utilization of wavelengths, is assign to each link. These cost parameters are used to calculate the cost vector of a path. In this multicost approach more than one path is calculated between two nodes and, as such, minimization and maximization can be used to arrive at the best path. This approach consists of two phases. The first phase uses an algorithm that is a generalization of the Dijkstras algorithm which obtains a set of candidate non-dominated lightpaths for a given connection request. In the second phase, a primary lightpath is selected to serve the connection request while a second lightpath, from the same set is selected as the backup path.

Experiments and/or analyses conducted
The authors conducted simulation experiments considering an all-

optical network where connections arrived dynamically and have to be served as they come. The blocking probability of several multicost based algorithms as a function of the number of available wavelengths, performing 1+1 and 1:1 protection were measured.

Results that the authors claimed to have achieved
The authors claim that the results show that in case of 1+1 protection, the sumQ and bestQ-bestQ policies result in similar blocking probability and in the case of 1:1 protection, the differences between the different protection policies are minimized. They also claim that there is a level of trade off between the level of protection (1+1, 1:1 and no protection). In addition, the authors claim that the usage of the worse case interference assumption for the selection of backup lightpath reduces the blocking probability.

Claims made by the authors
The authors claim that, based on their experimental observations, the joint selection of the primary and backup lightpaths is generally more preferable than selecting them separately. They also claim to show that the selection of backup lightpath, based on the worse case interference assumption can be quite beneficial for the survivability of the backup paths, when the network is heavily loaded. In addition, they claim that the problem is NP-complete.

Georgakilas, K., Katrinis, K., Tzanakaki, A., and Madsen, O. 2010. Performance evaluation of impairment-aware routing under single- and double-link failures. *Optical Communications and Networking, IEEE/OSA Journal 2, 8, 633-641.*

The problem which the researcher/authors addressed
The researchers address the problem of protecting impairment-aware WDM networks against failures by focusing on performance evaluation in impairment-aware routing under single and double link failures in identifying the primary and backup paths.

Previous work by other authors referred to by the authors
[Markadis and Tzanakaki 2008]

Shortcomings of previous work
The authors claim that the work of Markadis and Tzanakaki [2008] did not take into consideration double-link failures.

The new idea, algorithm, architecture, protocol, etc.
The authors developed a modular approach that divides the problem into several modules. The RWA problem is solved in two steps: routing and wavelength assignment (RWA) for the primary path and RWA for the backup path. Both steps are implemented using Dijkstras algorithm. The primary path for each request is computed by the impairment-aware RWA scheme and uses a first-fit algorithm based on the quality of the paths (a predefined BER threshold) for wavelength assignment. The backup path is computed using IA and minimum-hop routing and uses the weighted last-fit algorithm for wavelength assignment (also based on the BER threshold)

Experiments and/or analyses conducted
Four Experiments, based on simulations were evaluated using two network topologies: the COST 239 topology and the NSFNET topology. The scenarios are shown in the table below:

Scenario	Backup Path Routing	Reinforced Sharing
Sc1	IAR	Yes
Sc2	IAR	No
Sc3	min-hop	Yes
Sc4	min-hop	No

Table 1: Evaluation Scenarios Definitions, Performance evaluation of impairment-aware routing under single- and double-link failures [2010]. Georgakilas et al, page 637.

Results that the authors claimed to have achieved
The authors claim that they observed that when IAR was applied for the backup path computation, the total blocking probability for the COST 239 topology was much lower compared with the min-hop; for all load conditions, the blocking probability is reduced by more than 50 percent. In the NSFNET, the IAR also demonstrated reduction in blocking probability. They also claimed that when reinforced sharing is applied there is better resource utilization.

Claims made by the authors

The authors claim that when the quality of the formed paths is taking into account in the process of routing, the physical performance of the selected paths is shown to be better, compared with the traditional routing schemes that considers only bandwidth availability. They also claim that the impairment-aware routing scheme provides better performance under single- and dual-links failures. In addition, they claim that the consideration of impairments in the routing algorithm for both the primary and backup paths provides a reduced network blocking probability.

Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Naito, T. 2010. Survivable impairment-aware traffic grooming with dedicated path protection. *Optical Communication (ECOC), 2010 36th European Conference and Exhibition, 1-3.*

The problem which the researcher/authors addressed
The authors address the problem of protection of impairment-aware traffic-grooming WDM networks against single failures by focusing on efficient placement of equipment.

Previous work by other authors referred to by the authors
The authors did not refer to any previous work that attempt to solve the problem.

The new idea, algorithm, architecture, protocol, etc.
The authors developed a ROADM architecture that places a traffic grooming equipment or a regenerator at each node. They also developed a heuristic algorithm that is based on an auxiliary graph that consists of physical links (physical network topology), auxiliary links (routes that satisfied the impairments constraints) and virtual links (established lightpaths with sufficient spare capacity for the request).

A new backup lightpath is established by finding the shortest path on the auxiliary graph that is a link disjoint from the working path. Regenerators are then placed at all intermediate nodes along the backup path. Also, if there is spare capacity, the algorithm establishes a separate working lightpath and a separate disjoint backup

lightpath.

Experiments and/or analyses conducted
Experiments were conducted, via simulations, on a 100-node meshed network topology in which each link is assumed to have a bidirectional fiber. Line rates of 10 Gbps, 40 Gbps and 100 Gbps with different optical reach were used in the simulations.

Results that the authors claimed to have achieved
The authors claim that their results show that the cost of the grooming-only approach is less than the cost of the regenerator-only approach and the cost of the combined traffic grooming and regenerator placement is always lower. They also claim that based on the results: at low load, the 10 Gbps network has the lowest cost; at moderate load, the 40 Gbps network has the lowest cost; and at high load, the 100 Gbps with reachability of 8 hops has the lowest cost.

Claims made by the authors
The authors claim that the efficient placement of traffic grooming and regenerators together for establishing survivable lightpaths reduces cost. They also claim that as the traffic load increases, the network can further be improved by increasing the line rate.

Azodolmolky, S., Klinkowski, M., Pointurier, Y., Angelou, M., Careglio, D., Sol-Pareta, J., and Tomkos, I. 2010. A novel offline physical layer impairments aware RWA algorithm with dedicated path protection consideration. *Journal of Lightwave Technology, 28, 20, 3029-3040.*

The problem which the researcher/authors addressed
The researchers address the problem of protecting impairment-aware WDM networks against failures by focusing on offline physical layer impairment aware routing with dedicated path protection consideration.

Previous work by other authors referred to by the authors
The authors do not refer to any previous work that attempts to solve the problem.

The new idea, algorithm, architecture, protocol, etc.
In this performance evaluation, the authors developed three algorithms. They enhanced two existing IA-RWA algorithms (the RS-RWA algorithm and an ILP-based RWA algorithm) that did not considered dedicated path protection. The two offline IA-RWA algorithms were extended to consider dedicated path protection. The performances of these two algorithms were compared with that of a new IA-RWA algorithm (the Rahyab algorithm). The new algorithm uses a demand pre-processing module to order the traffic demands and a process to select a lightpath form the candidate lightpath list. Traffic demands can be protected or unprotected.

Experiments and/or analyses conducted
Experiments were conducted based on simulations that used the Deutsche Telekom National Network (DTNet) which 14 nodes and 23 bidirectional links, with an average node degree of 3.29.

Results that the authors claimed to have achieved
The authors claim that their results show that the performance of the ILP-RWA-LU (1 SP) is better than the original ILP-RWA algorithms (both 1 SP and 2 SP). They also claim that their results indicate that increasing the number of candidate shortest paths also increases the blocking rate of ILP-RWA and ILP-RWA-LU algorithms.

Claims made by the authors
The authors claim that their enhancements to the RS-RWA heuristic (that is, RS-RWA-Q) reduced the blocking rate of demands by an average of 35 percent from different loads compared to the original scheme (RS-RWA); the performance of ILP-RWA-LU (1 sp) formulation (enhanced IRL-RWA) is also improved by 71 percent; and the Rehab algorithm performs better than the two algorithms with respect to the blocking rate performance metric.

Gao, C., Cankaya, H., Patel, A., Jue, J., Wang, X., Zhang, Q., Palacharla, P., and Sekiya, M. 2012. Survivable impairment-aware traffic grooming and regenerator placement with connection-

level protection. *Optical Communications and Networking, IEEE OSA Journal. 4, 3, 259-270.*

The problem which the researcher/authors addressed
The problem identified by the authors is protection of impairment-aware optical WDM networks against failures by focusing on improving utilization of network resources.

Previous work by other authors referred to by the authors
In 2010, a subset of the authors proposed a combined traffic grooming and regeneration placement approach to support all traffic demands with minimum cost. [Patel et al 2010].

Shortcomings of previous work
The authors claim that the solution of Patel et al [2010] may not be cost or resource efficient for cases in which the lightpath is not fully occupied. The new idea, algorithm, architecture, protocol, etc. The authors developed a reconfigurable optical add-drop multiplexer (ROADM) node architecture. They state that this architecture has an all-optical wavelength switch fabric coupled with an electrical backbone, which together connects the various grooming and regenerator equipment.

The authors present two algorithms (a dedicated connection-level protection algorithm and a shared connection-level protection algorithm) that use auxiliary graphs that take into consideration the weight and residual capacity of each type of link. They note that, in each algorithm, the auxiliary graph is first generated and used to select the solution that generates the minimum network cost.

Experiments and/or analyses conducted
The authors conducted experiments for both algorithms, on two simulated networks. A randomly generated 100-node network topology, whose average node degree is 4, and a 14-node NFS network with a node degree of 2.7.

Results that the authors claimed to have achieved
The authors claim that their results show that when comparing connection-level protection with lightpath-level protection, among

other parameters, connection-level protection achieves lower cost, but has a higher signaling cost when a lightpath failure occurs.

Claims made by the authors
The authors claim that their stimulation results show that their approach outperforms a lightpath-level protection approach, in terms of network cost. They also claim to show that a network with higher line rate and longer optical reach can reduce the network cost, when the traffic load increases.