A Survey on Static Impairment-Aware Routing and Wavelength Assignment Heuristics in Optical WDM Networks

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Physical layer impairments in optical fibers degrade the quality of the optical signal as it propagates along a lightpath. This leads to an increase in the Bit Error Rate (BER) of the optical signal and the corresponding lightpath becomes infeasible for communication if the BER crosses a certain threshold limit. Traditional RWA approaches assume an ideal physical layer medium and ignore the effects of physical impairments on the lightpath feasibility. This aspect of network design has gained significant attention in the last few years. The static lightpath demand version of the problem poses additional complexity as far as the impairments are concerned. Integer Linear Programming (ILP) based solutions prove to be computationally intensive in larger network instances. This has led to the development of a series of interesting heuristics to tackle the problem of Impairment-Aware Routing and Wavelength Assignment (IA-RWA) in optical WDM networks. This survey presents a detailed analysis of the IA-RWA heuristics from various research publications, to aid in better understanding of the research in optical WDM networks.

Categories and Subject Descriptors: []:

General Terms: Lightpath, Routing and Wavelength Assignment (RWA), Impairment-Aware RWA (IA-RWA)

Additional Key Words and Phrases: Physical Layer Impairments, Quality-Factor (Q-Factor), Quality of Transmission (QOT), Bit Error Rate (BER)

Contents

1. INTRODUCTION

The quality of an optical signal, propagating along a lightpath, is degraded due to a number of physical layer fiber impairments. Lightpaths which do not meet the required Quality of Transmission (QOT) are considered unsuitable for communication. The Routing and Wavelength Assignment (RWA) approaches till early 2005 assumed an ideal physical layer medium and ignored the effects of these impairments on lightpath establishment. Impairment-Aware RWA (IA-RWA) has been a topic of intense research in the last few years. The static version of IA-RWA has particularly received greater attention in the research community because of the additional complexity involved in establishing lightpaths when all the requests are known in advance. Considering the computational complexity of ILP based approaches for larger network instances, a number of heuristics have been developed to solve the IA-RWA problem.

This survey summarizes research on various interesting heuristics on Static IA-RWA. The research papers for this survey were found using Google Scholar, ACM, LNCS and IEEE. A total of 20 papers were found to be on the topic of Static IA-RWA of which 9 are conference papers, 9 are journal papers and 2 are books from Lecture Notes in Computer Science. The heuristics proposed in 10 of these 20 papers, form the basis of this survey.

The heuristics summarized in this survey are classified into two categories depending on whether optical signal regenerators are used in the network. Translucent optical networks employ sparsely located optical regenerators whereas transparent networks involve no regenerators. The objective in translucent networks is to use a minimum number of regenerators to route the lightpaths. Whereas, the objective in transparent networks is to route as many lightpaths as possible that meet the QOT requirements. Of the 10 research papers that form the basis of this survey, 3 papers are on IA-RWA heuristics in translucent optical networks (Section 2 of the survey) and 7 papers are on IA-RWA heuristics in transparent optical networks (Section 3 of the survey).

Section 2 reviews the following research papers: Subsection 2.1: [Ezzahdi et al. 2006] and [Garcia-Manrubia et al. 2011]. Subsection 2.2: [Manousakis et al. 2009].

Section 3 reviews the following research papers: Subsection 3.1: [Bakri et al. 2009], [Pavon-Marino et al. 2009], [Azodolmolky et al. 2010] and [Sengezer and Karasan 2010]. Subsection 3.2: [Monoyios et al. 2009]. Subsection 3.3: [Keles et al. 2010a] and [Keles et al. 2010b].

2. PHYSICAL IMPAIRMENT-AWARE ROUTING AND WAVELENGTH ASSIGNMENT HEURISTICS IN TRANSLUCENT OPTICAL NETWORKS

This section deals with IA-RWA heuristics in translucent optical networks, in which the optical signal degradation due to physical layer impairments is handled using 3R regenerators that restore the signal strength periodically. Since every regeneration involves Optical-to-Electronic-to-Optical (OEO) conversion of the signal, it is a very costly step. Therefore, the objective of a static IA-RWA heuristic in such networks is to minimize the number of 3R regenerators that will be deployed and used. The heuristics in this section are further divided into two groups based on whether the regenerator placement step is performed before or after the RWA phase. Ezzahdi et al. [2006] were the first to attempt this problem and their LERP heuristic is considered a milestone in this survey.

2.1 Routing and Wavelength Assignment Followed by Q-factor Evaluation and Regenerator Placement

This subsection deals with heuristics that perform the RWA phase prior to the regenerator placement. The RWA phase in these heuristics is same as any other traditional approach. After the RWA is performed, the established lightpaths are checked for their feasibility in terms of the physical layer impairments followed by the regenerator placement phase to route the infeasible lightpaths.

2.1.1 *Lightpath Establishment with Regenerator Placement (LERP) Heuristic.* Ezzahdi et al. [2006] appear to be the first researchers to address the problem of Static Impairment-Aware Routing and Wavelength Assignment and hence the authors do not refer to any specific previous work.

Ezzahdi et al. [2006] propose a new Static Impairment-Aware Routing and Wavelength Assignment (IA-RWA) algorithm called LERP (Lightpath Establishment with Regenerator placement) that is an improvement over a previous algorithm from the literature which is referred to as sLERP (Simple LERP) in this paper. sLERP algorithm proceeds in 2 phases namely the RWA phase and the QOT-Test phase.

The RWA phase of sLERP is only responsible for assigning a route and a wavelength to the connection requests between various (source, destination) pairs. The effect of physical layer impairments is not yet considered in this phase. The RWA phase intially uses a sequential RWA algorithm, that is based on the k-shortest path concept, to establish the lightpaths. Some of the connection requests could be rejected or blocked due to unavailability of wavelength channels. The lightpaths established using the sequential RWA algorithm are therefore rerouted using a Random Search (RS) based algorithm in order to minimize the number of rejected lightpath requests.

The QOT-Test Phase of sLERP deals with the effect of physical layer impairments on the feasibility of a lightpath. For each of the lightpaths obtained from the RWA phase, the Q-factor value is evaluated at each of the intermediate nodes along the route of the lightpath. If the Q-factor at any particular node i is found to be below the prescribed threshold limit for the network then a regenerator is placed at the previous node i-1. This is continued till the destination node is reached.

In LERP algorithm the RWA phase is exactly same as that of sLERP. The improvement is made in the QOT-Test phase. In the QOT-Test phase of LERP when the Q-factor of a lightpath at any of the intermediate nodes (say i) goes below the threshold, a regenerator is placed at the previous node i-1 and the remaining portion of the lightpath (i,destination) is put into a new traffic matrix. The lightpath (source, i-1) is recorded as established. Once the Q-factor evaluation is done for all the lightpaths in a similar way, the newly obtained traffic matrix is again fed back to the RWA phase. This loop of RWA and QOT-Test phases is repeated till all the lightpaths meet the Q-factor requirements. The basic objective of creating a new traffic matrix and sending it back to the RWA phase is to try to establish a route for a lightpath that uses the least number of regenerator nodes.

Ezzahdi et al. [2006] state that they have compared the performance of LERP and sLERP algorithms in terms of the number of rejected connection requests and the number of regenerator nodes used.

Ezzahdi et al. [2006] state that the experiments that they conducted clearly indicate that the LERP algorithm achieves lesser number of rejected lightpath requests and regenerators when compared to sLERP. The authors also state that LERP and sLERP algorithms achieve similar performance for higher number of wavelength channels in the fiber links.

Ezzahdi et al. [2006] claim that their approach is unique because it takes into account the simultaneous impact of four major physical layer impairments namely Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), Amplified Spontaneous Emission (ASE) and Non-Linear Phase Shift, while evaluating the Q-factor of the lightpaths.

2.1.2 *Separately Considering Linear and Non-Linear Impairments in Static IA-RWA.* Physical layer impairments are classified broadly into two categories namely Linear and Non-Linear. Linear impairments are those that affect the same lightpath which generated them. Non-Linear impairments are those that are generated by other existing lightpaths in the network and affect a particular lightpath. Garcia-Manrubia et al. [2011] address the problem of Impairment-Aware Routing and Wavelength Assignment with regenerator placement (IA-RWA-RP) under a static traffic scenario separately considering the impact of linear and non-linear physical layer impairments.

The authors refer to previous work by Ezzahdi et al. [2006] and Manousakis et al. [2009]. Garcia-Manrubia et al. [2011] state that the three phase heuristic proposed by Manousakis et al. [2009] is not able to effectively minimize the number of blocked connection requests.

Garcia-Manrubia et al. [2011] formulate an Integer Linear Programming formulation (ILP) for the Linear IA-RWA-RP problem (that considers linear impairments only) in order to obtain the optimal solution. The authors also propose an ILP based algorithm, called LS (Lightpath Segmentation) Algorithm, to solve the Linear IA-RWA-RP problem. LS algorithm starts off by constructing a set of candidate lightpaths for every (source,destination) pair in the network. This set is further divided into two subsets based on whether a lightpath needs a regenerator or not. Then the algorithm iterates through the subset containing those lightpaths that require regenerators and splits each of them into semilightpaths (semilightpath is a portion of a bigger lightpath that does not need regenerators). There can be potentially a number of ways of splitting a non-transparent lightpath into semi-lightpath segments and therefore a set of candidate segmentations are created for every such lightpath. Finally, The two subsets and the generated segmentation sets are given as inputs to an Integer Linear Programming(ILP) formulation that solves the Routing and Wavelength Assignment problem where the objective function is to minimize the number of regenerators used and the number of blocked connection requests.

Garcia-Manrubia et al. [2011] also propose a Three Step heuristic for the linear IA-RWA-RP problem in larger network scenarios. The first step only considers the routing part of lightpaths. Routes with minimum number of intermediate hops are chosen to establish the lightpaths. The second step involves wavelength assignment for the routes setup in the first step. During this step if the wavelength continuity constraint cannot be satisfied for a particular lightpath then 3R regenerators (used as wavelength converters) are placed accordingly. Finally in the third step the lightpaths from step 2 are evaluated for their Q-factor values. If the Q-factor for a certain lightpath goes below the prescribed threshold, then it is divided into semi-lightpath segments and regenerators are placed accordingly. The heuristic continues till all lightpaths are established.

For the Non-Linear IA-RWA-RP problem, Garcia-Manrubia et al. [2011] propose a heuristic called Iterative Regenerator Placement (IRP) that is an extension of the three step heuristic proposed for the linear case. The first two steps of the IRP heuristic are same as that of the linear heuristic, with one small difference in the wavelength assignment step. In the wavelength assignment stage though regenerators are placed (used as wavelength converters), the wavelengths are not assigned to the lightpaths. Finally in step 3, the lightpaths and regenerators placed in step 2 are given as an input to a Wavelength Assignment ILP that takes into account the effects of other lightpaths (non-linear impairments). The objective of this ILP is to minimize the noise variance caused by non-linear impairments. After the ILP ends, the Q-factor of every lightpath is tested and if all lightpaths have satisfactory Q-factor values then the heuristic ends. Otherwise, the lightpath is split into semilightpath segments and regenerators are placed accordingly.

Garcia-Manrubia et al. [2011] state that they performed separate evaluations for the Linear and Non-Linear IA-RWA-RP problems. For the linear case they compared their heuristics (the LS algorithm and the Three step heuristic) with the LERP heuristic proposed by Ezzahdi et al. [2006]. For the Non-Linear IA-RWA-RP case the authors compared their IRP heuristic with the PH-ILPmax algorithm proposed by Manousakis et al. [2009].

Garcia-Manrubia et al. [2011] have tabulated the regenerator cost values (for different values of wavelength channels per fiber and other network parameters) obtained for all the linear and non-linear heuristics considered for evaluation (namely LS algorithm, Three step heuristic, LERP algorithm, IRP heuristic and PH-ILPmax algorithm). The table also shows the percentage of lightpath blocking for the LERP and PH-ILPmax heuristics. Since the linear and non-linear heuristics proposed by Garcia-Manrubia et al. [2011] offer zero blocking of lightpaths, the table does not include any blocking values for them.

Garcia-Manrubia et al. [2011] claim that they are the first to address the IA-

RWA-RP problem by separately considering the impact of linear and non-linear physical layer impairments. The authors state that their Linear Heuristics (namely LS algorithm and Three Step Heuristic) clearly outperform the LERP heuristic proposed by Ezzahdi et al. [2006]. They also claim that their IRP non-linear heuristic outperforms the PH-ILPmax algorithm proposed by Manousakis et al. [2009].

Year	Authors	Title	Papers Referred to	Major Contribution
2006	Ezzahdi et al	LERP: a quality of transmission dependent heuristic for routing and wavelength assignment in hybrid wdm networks	None	First paper to present an IA-RWA heuristic in translucent optical Networks.
2011	Garcia-Manrubia et al	Offline impairment-aware rwa and regenerator placement in translucent optical networks	Ezzahdi et al. 2006 and Manousakis et al. 2009	Presents two new heuristics separately considering Linear and Non-Linear impairments. The proposed heuristics offer better performance compared to Ezzahdi et al. 2006 and Manousakis et al. 2009.

Table I. Summary of papers reviewed in Subsection 2.1

2.2 Regenerator Placement Followed by Impairment-Aware Routing and Wavelength Assignment

This subsection deals with an IA-RWA heuristic proposed by Manousakis et al. [2009], which is interesting in the sense that the regenerator placement/assignment is performed before the IA-RWA phase. Manousakis et al. [2009] address the problem of lightpath establishment in translucent optical networks considering Regenerator Placement and Regenerator Assignment as sub-problems. The fundamental objective is to minimize the overall network cost by reducing the number of regenerators deployed/used.

The authors refer to previous work by Ezzahdi et al. [2006] and Christodoulopoulos et al. [2009]. But, no Shortcomings of previous work are mentioned.

The static Impairment-Aware lightpath establishment approach proposed by Manousakis et al. [2009] proceeds in three phases and considers two different types of input settings. One in which only a network topology and static traffic matrix are given and the algorithm is required to identify the regenerator sites and the number of regenerators to be placed at these sites, before proceeding with Routing and Wavelength Assignment. The second input setting assumes a given placement of regenerators and the objective is to select the specific regenerators to be used by the lightpaths. These two input settings are often referred to in the literature as Regenerator Placement and Regenerator Assignment respectively.

In the first phase of the algorithm the Q-factor values of all the lightpaths are computed. Based on the obtained Q-factor values the lightpaths are divided into transparent (that do not need regenerators) and non transparent (that need regenerators) categories. Lightpaths in the non-transparent category are split up into transparent lightpath segments by using regenerators. Manousakis et al. [2009]

propose four Greedy technique based heuristics namely Virtual-Hop Shortest Path (VH), Physical-Hop Shortest path (PH), Physical length shortest path (PL) and Adjusted-Virtual-Hop (AVH), to solve the regenerator placement/assignment problem. The authors also propose an Integer Linear Programming (ILP) based algorithm for the regenerator placement/assignment problem. The ILP based algorithm internally uses each of these four Greedy heuristic techniques to find k shortest paths. The ILP uses three different objective functions namely the maximum number of regenerators among all nodes, the total number of regenerators used and the number of regeneration sites. Based on the objective function that is optimized the ILP is referred to as ILPmax, ILPsum and ILPsites respectively. At the end of this phase all the non-transparent lightpaths are converted into transparent connection requests by using regenerators.

The transparent lightpath requests from phase one are given as input to phase two which performs Impairment-Aware Routing and Wavelength assignment (IA-RWA). In this phase, the authors use the ILP based IA-RWA algorithm proposed by Christodoulopoulos et al. [2009]. Manousakis et al. [2009] state that any IA-RWA algorithm could be used in phase two, but they are of the view that the algorithm proposed by Christodoulopoulos et al. [2009] is particularly more suitable because it provides the advantage of incorporating the interference among the lightpaths (non-linear impairments). Some of the lightpath requests in phase two are blocked either due to unavailability of wavelengths or due to unacceptable quality of the lightpath. Finally in phase three the blocked connection requests from phase two are rerouted.

Manousakis et al. [2009] state that they conducted simulation experiments separately considering the regenerator placement and regenerator assignment scenarios. The authors state that they have used a combination of the ILP based algorithms (ILPmax, ILPsum and ILPsites) and the Greedy heuristics (VH, PH, PL and AVH) for performance evaluation. The performance evaluation metrics used by the authors include the blocking ratio of lightpath requests, total number of regenerators used, total number of regeneration sites and the number of wavelength channels used to establish lightpath requests.

The authors state that the experiments which they conducted indicate that for both regenerator placement and assignment problems, the PH heuristic and the PH-ILPmax algorithm exhibit relatively good performance in terms of the lightpath blocking ratio. But, they also state that these heuristics perform poorly in terms of the number of regenerators used in the case of regenerator placement problem. The authors also state that the PH-ILPmax combination consumes the least number of wavelengths in order to establish all the lightpath requests with zero blocking.

Manousakis et al. [2009] do not make any claims with respect to the contribution that they have made.

Year	Authors	Title	Papers Referred to	Major Contribution
2009	Manousakis et al	Offline impairment-aware routing and wavelength assignment algorithms in translucent wdm optical networks	Ezzahdi et al. 2006 and Christodoulopoulos et al. 2009	A new Static IA-RWA heuristic for translucent networks.

Table II. Summary of papers reviewed in Subsection 2.2

3. PHYSICAL IMPAIRMENT-AWARE ROUTING AND WAVELENGTH ASSIGNMENT HEURISTICS IN TRANSPARENT OPTICAL NETWORKS

A total of 7 papers on static IA-RWA heuristics in transparent networks are presented in this section. In transparent networks the signal propagating along a lightpath always remains in the optical domain (no OEO conversion) and no regenerators are deployed in the network. As a result, some of the established lightpaths could be rejected if they do not meet the quality of transmission requirements. Hence, the objective in such networks is to intelligently route the lightpaths so that only a small number of them are blocked due to physical layer impairments.

3.1 Solving the Impairment-Aware Routing and Wavelength Assignment Problem Using Iterative Search Based Heuristics

This subsection deals with IA-RWA heuristics in transparent networks, that perform multiple iterations of the RWA and Q-factor evaluation phases, making modifications from iteration to iteration, in order to arrive at a solution that offers the least lightpath blocking. Minimizing the lightpath blocking, remains the common problem statement for all the heuristics presented in this subsection.

3.1.1 *Selecting Paths with the Worst QOT to Minimize the Blocking Ratio.* Bakri et al. [2009] propose three new Impairment-Aware Routing and Wavelength Assignment (IA-RWA) heuristics (given a set of static lightpath demands). The authors do not refer to any previous work. In all the three algorithms, the authors use their own analytical model to evaluate the Q-factor of the established lightpaths.

The first algorithm is called QPSA (Quality Path Selection Algorithm). As a preprocessing step, K-shortest paths are computed for every (source, destination) pair in the given network topology. There could be multiple lightpaths that need to be setup for the same (source, destination) pair. Hence, it is important that the number of available wavelengths on the selected route/path should be greater than or equal to the number of lightpaths requested between the pair of nodes. Each (source, destination) pair, for which lightpath(s) are to be established, the set of corresponding K-shortest paths are scanned sequentially and the Q-factor values of every (path, wavelength) combination are computed. The first route/path, that offers the required quality of transmission (QOT) and the required number of wavelengths, is selected to establish the lightpath and the network status is updated accordingly. If a path with the required QOT is not found, then the lightpath request is considered as rejected.

The second algorithm called WQPSA (Worst Quality Path Selection Algorithm) is an extension of QPSA. In WQPSA, instead of selecting the first path that offers the required QOT, a set of admissible paths, that offer the required QOT, is computed first. From this set, the (path, wavelength) combinations whose Q-factor values are close to the threshold (i.e. with higher or worst Q-factor values) are given priority while making the selection. This criteria mainly helps in minimizing the number of rejected lightpath requests because those (path, wavelength) combinations with lesser Q-factor values are preserved for further requests.

The third algorithm called SWQPSA (Shortest Worst Quality Path Selection Algorithm), is a further extension to the WQPSA algorithm. This algorithm proceeds in 3 phases, in which phase 1 and phase 2 correspond to the QPSA and WQPSA algorithms respectively. At the end of phase 2, unlike in the case of WQPSA where the network status is updated with the established lightpath, in SWQPSA the lightpaths are only assumed to be established and among these lightpaths the one which has the shortest path only is actually treated as established. The remaining lightpaths are again fed back to phase 1 as lightpath requests. This process is repeated until all the lightpaths are established. The main purpose of following this process is to establish first, those lightpaths which consume the minimum number of network resources, so that it finally leads to a minimum number of blocked lightpath requests.

Bakri et al. [2009] state that they compared the performances of QPSA, WQPSA and SWQPSA with that of a plain RWA (which does not consider impairments) referred to as SPSA (Shortest path Selection Algorithm) in the paper. The authors state that they have used the lightpath rejection ratio as their fundamental performance evaluation metric.

The authors state that the experiments that they conducted clearly indicate that the plain RWA (SPSA) achieves much lesser lightpath rejection ratio compared to their proposed algorithms. They are of the view that this trend emphasizes the importance of considering physical layer impairments while performing RWA. Also, they state that SWQPSA is the worst performing among the three IA-RWA algorithms.

Bakri et al. [2009] claim that they are the first to consider the simultaneous impact of four important physical layer impairments (namely Chromatic Dispersion, Polarization Mode Dispersion, Optical Signal to Noise Ratio and Nonlinear Phase Shift) while performing RWA in transparent optical networks.

3.1.2 *Maximizing the Number of Established Lightpaths Using an Iterative Search Based Heuristic.* Pavon-Marino et al. [2009] propose two new heuristic approaches to solve the IA-RWA problem in transparent optical networks namely: The Global Search Algorithm and the Sequential Heuristic Approach.

The authors refer to the previous work by Markidis et al. [2007]. They state that the IA-RWA approach proposed by Markidis et al. [2007] does not perform a collective wavelength assignment for all the lightpaths and hence does not consider the actual interference due to other lightpaths.

The Global Search algorithm is an iterative search based algorithm that internally uses a fundamental Core Algorithm and three different Binary Integer Linear Programming (BILP) formulations to establish lightpaths with impairment-aware constraints. The Global Search algorithm proceeds in four phases. The first phase is a preprocessing stage in which two important parameters are computed namely: S_{IA}which is the set of (path, wavelength) pairs whose static Q-factor values (i.e. considering only linear impairments) are higher than the prescribed threshold (Q_{Th}). D is a two dimensional degradation matrix, that gives the degradation in the Q-factor of every lightpath due to others.

Phase 2 finds an initial RWA solution (from the set S_{IA}) using a BILP which does not use any impairment-aware constraints. The Q-factor values of the lightpaths in the obtained initial RWA solution are measured. In the obtained RWA solution, the number of lightpaths whose Q-factor values are above Q_{Th} is set as a lower bound (Llb) and the total number of lightpaths is set as an upper bound (Lub). The main idea of using these bounds is that, finally at the end of the algorithm the number of lightpaths which are successfully established (that meet the Q-factor threshold limit) should be between Llb and Lub.

Phases 3 and 4 are used to find an RWA solution with exactly a certain number of lightpaths (L) that meet the Q-factor threshold. The main objective of these phases is to maximize the value of L. Phase 3 uses a top-down approach in which it starts with L = Lub and gradually reduces its value till a solution is found. Phase 4 uses a bottom up approach in which it starts with L = Llb and increases the value of L selectively. The values of L visited during phase 3 are recorded and not repeated during phase 4.

The Core algorithm is fundamental to phases 3 and 4 of the Global Search algorithm. The Core algorithm is used to establish an exact number of lightpaths (say L, as prescribed by the phases), with the objective of maximizing the number of lightpaths among L that meet the QOT threshold. The Core algorithm starts by finding an initial solution using a BILP. This BILP does not take into account the non-linear or dynamic physical impairments and just tries to minimize the sum of static Q-factor values of the established lightpaths. This initial solution is refined in a certain number of fixed iterations. In each iteration, two sets of (path,wavelength) pairs are created. The first set contains those pairs that will remain active in the solution of the current iteration and the second set contains those pairs that will remain inactive. Each iteration makes a fixed number of changes to the solution of the earlier iteration. Each iteration uses a BILP in turn to establish the lightpaths. This final BILP takes into account the non-linear impairments as well.

The Sequential heuristic starts by finding the shortest path for every source destination pair in the topology, for which lightpaths are to be established. The product of the shortest path length and the number of lightpaths for each (source,destination) pair is computed. The (source, destination) pairs are arranged in the increasing and decreasing order of these product values. Then the set of ordered (source, destination) pairs is scanned sequentially and for each pair the required number of lightpaths are established in the following way: Initially the set S_{IA} is constructed, similar to the Global Search algorithm. A (path, wavelength) pair is removed from this set accordingly if this wavelength clashes with those of the existing lightpaths. Then they are ordered as per the increasing length of the path. The first 10 of these are selected and are added to the existing set of established lightpaths one at a time and the Q-factors of all the lightpaths are measured. If the worst Q-factor among all of them is less than the threshold then that particular (path, wavelength) pair is removed. Proceeding in this manner, the appropriate (path, wavelength) pairs are selected to meet the required lightpath requests. If no pair is found, then the corresponding lightpath request is blocked.

Pavon-Marino et al. [2009] state that they compared the performances of the Global Search algorithm, the Sequential Heuristic and the transparent IA-RWA variation of the LERP heuristic (referred to as sLERP) proposed by Ezzahdi et al. [2006]. The authors state that they used the blocking ratio of lightpath requests as their fundamental performance evaluation metric.

Pavon-Marino et al. [2009] state that the Global Search algorithm achieves the lowest blocking rate among all the heuristics (in different topologies and wavelength settings), followed by the Sequential heuristic and sLERP.

Pavon-Marino et al. [2009] claim that their IA-RWA approaches clearly outperform the sLERP heuristic.

3.1.3 *Considering Dedicated Path Protection in Static IA-RWA* . Azodolmolky et al. [2010] enhance the heuristic approach proposed by Ezzahdi et al. [2006] and also enhance an ILP based RWA algorithm from the literature by adding impairment aware constraints (enhanced ILP is called as ILP-RWA-LU in the paper). Finally the authors propose a new IA-RWA heuristic for transparent or all-optical networks. Additionally, the authors also propose slightly modified versions of their heuristics to consider the dedicated path protection requirement for certain lightpath requests.

The authors also refer to the previous work by Manousakis et al. [2009]. But, no shortcomings of previous work are mentioned.

The IA-RWA heuristic proposed by Ezzahdi et al. [2006] (called LERP) proceeds in two phases namely the RWA phase and the QOT Test phase. The functionality of the RWA phase is just to assign a tentative route and a wavelength for each lightpath request. The lightpaths established in the RWA phase are then fed to the QOT-Test phase which handles the functionality of evaluation of impairments for the lightpaths and proceeds with the placement of regenerators accordingly. Azodolmolky et al. [2010] extend the RWA phase of the LERP heuristic (the extended version is called RS-RWA-Q) to include the evaluation of physical layer impairments in it. In RS-RWA-Q heuristic k-shortest paths are computed for each pair of (source, destination) nodes and the lightpath requests are ordered randomly. Then a sequential RWA is performed to establish the connection requests. After the RWA is done, the Q-factor values of all the established lightpaths are measured. A lightpath with an inadmissible Q-factor value is considered as rejected. A lightpath could also be rejected during the RWA due to the unavailability of a required wavelength. The RWA and Q-factor evaluation stages are repeated for different random orderings of the lightpath requests and finally the RWA solution which offers the lowest number of rejected lightpaths is selected. The authors also add a dedicated path protection requirement to the RS-RWA-Q heuristic by putting the protected lightpath requests before others while ordering them in the first step.

The authors finally propose a new IA-RWA heuristic (called "Rahyab") for transparent optical networks. As a preprocessing step, the shortest paths are computed for each source destination pair and then the lightpath requests are arranged in the decreasing order of the length of the shortest path between the corresponding source and destination nodes. A layered network graph is created using the given network topology. This layered network graph contains the entire topology replicated w times in the form of layers, where w represents the maximum number of available wavelengths on all fiber links. For each lightpath request candidate routes are established in each of these w wavelength layers. Then the authors evaluate the Q factors values of each of these candidate paths (Qp) using a customized Q-factor evaluation tool. The combined Q-factor (say Qc) of all the already established lightpaths is also computed. Finally, the candidate lightpath with the highest non-negative (Qc - Qp) value is considered as established and the network topology is updated to reflect the change. If the algorithm is unable to establish a lightpath request, then it is considered as rejected. Azodolmolky et al. [2010] have also proposed a slightly modified version of their Rahyab heuristic to include the dedicated path protection requirement for certain lightpath requests.

Azodolmolky et al. [2010] state that they compared the performance of their enhanced heuristic (RS-RWA-Q) with the plain RS-RWA proposed by Ezzahdi et al. [2006]. The authors also state that they compared the performance of their new heuristic (Rahyab) with the RS-RWA-Q and ILP-RWA-LU enhancements.

The authors state that they used blocking rate of lightpath demands as their fundamental performance evaluation metric. The blocking rates (of all the heuristics), for different values of network loads and maximum number of wavelength channels per fiber link, were represented graphically.

Azodolmolky et al. [2010] claim that their enhanced RS-RWA-Q heuristic offers 35% lesser blocking rate (on an average for different loads) compared to the RS-RWA proposed by Ezzahdi et al. [2006]. They also claim that their Rahyab heuristic performs even better than their enhancements.

3.1.4 *Minimizing the Lightpath Blocking Ratio Using Iterative Demand Pre-Processing.* Sengezer and Karasan [2010] propose an IA-RWA Integer Linear Programming (ILP) formulation (to find the optimal solution) for small and medium sized transparent networks followed by a new heuristic called "ROLE" (Reordered Lightpath Establishment Algorithm) for large size transparent networks.

The authors refer to the previous work by Ezzahdi et al. [2006], Azodolmolky et al. [2009] and Monoyios et al. [2009].The authors state that the IA-RWA approach proposed by Azodolmolky et al. [2009] does not consider different orderings of the lightpath requests while performing the RWA. The authors are of the view that multiple orderings of the lightpath requests could improve the total number of established lightpaths that meet the QOT requirements.

ROLE heuristic proceeds in three phases namely: 1. Routing and Wavelength Assignment (RWA), 2. Rerouting and 3. Reordering. The fundamental objective of ROLE is to try different orderings of the lightpath requests using multiple RWA schemes to establish a maximum number of lightpaths that meet the QOT constraints. As a preprocessing step, the K-shortest paths are computed for every (source, destination) pair in the topology.

In the RWA phase three different types of routing schemes are used namely: the Shortest path First(SPF), the Shortest Widest Path First (SWPF) and the Widest Shortest Path First (WSPF). The width of the path here refers to the number of available or free wavelengths on the path. Also, three different wavelength assignment schemes are considered namely: the First Fit with BER constraint (FFB), the Minimum BER (MB) and the Maximum-Minimum BER (MMB). A combination of these routing and wavelength assignment schemes are tried to establish the lightpath requests. In addition to these schemes two exhaustive RWA schemes called the Exhaustive minimum BER (E-MB) and the Exhaustive Minimum-Maximum BER (E-MMB) are also proposed. These schemes are exhaustive in the sense that they do not stop if a particular wavelength is found. They try all possible wavelengths and select the one which offers the minimum BER for the established lightpath.

The Rerouting phase comes after the RWA is done. In this phase, attempts are made to reroute the blocked lightpaths from the RWA phase. Two classifications of the blocked lightpaths are made namely: The BER-blocked lightpaths (blocked due to BER constraints) and the Wavelength-blocked lightpaths (blocked due to unavailability of free wavelengths). The BER-blocked lightpaths are rerouted first followed by the Wavelength-blocked lightpaths.

The Reordering phase comes as a final step, in which the lightpaths that could not be established in the earlier two phases are marked and placed in the front of the lightpath request queue. The solution from the earlier phases is saved or recorded. This new sequence of lightpath requests are again fed to the RWA phase. This process is repeated until every lightpath request is established in some or the other iteration. Finally, the solution which offers the highest number of Q-feasible lightpaths is selected.

Sengezer and Karasan [2010] state that they measured the performance of different combinations of the routing schemes (SPF, SWPF, and WSPF) and the wavelength assignment schemes (FFB, MB, MMB, E-MB and E-MMB). The authors state that they also compared the performance of the ROLE heuristic with the POLIO-RWA heuristic proposed by Azodolmolky et al. [2009]. The authors state that they used, the percentage of established lightpaths, as their performance evaluation metric.

The authors state that the experiments they conducted indicate that the SWPF scheme gives the best performance among the routing schemes. They also state that MB and MMB wavelength assignment schemes offer similar performance better than the FFB scheme.

The authors claim that the ROLE heuristic clearly outperforms the POLIO-RWA heuristic proposed by Azodolmolky et al. [2009].

Year	Authors	Title	Papers Referred to	Major Contribution
2009	Bakri et al	Static lightpath establishment with transmission impairments consideration in wdm all-optical networks	None	First paper to consider the impact of four major physical impairments in an IA-RWA heuristic for transparent networks.
2009	Pavon-Marino et al	Offline impairment aware rwa algorithms for cross-layer planning of optical networks	Markidis et al. 2007	Presents two new IA-RWA heuristics in transparent networks.
2010	Azodolmolky et al	A novel offline physical layer impairments aware rwa algorithm with dedicated path protection consideration	Ezzahdi et al. 2006 and Manousakis et al. 2009	Enhances the heuristic proposed by Ezzahdi et al. [2006]. Offers lesser blocking ratio compared to Ezzahdi et al. 2006.
2010	Sengezer and Karasan	Static lightpath establishment in multilayer traffic engineering under physical layer impairments	Ezzahdi et al. 2006, Azodolmolky et al. 2009 and Monoyios et al. 2009	Presents a new IA-RWA heuristic for transparent networks. Outperforms the heuristic proposed by Azodolmolky et al. [2009].

Table III. Summary of papers reviewed in Subsection 3.1

3.2 Solving the Impairment-Aware Routing and Wavelength Assignment Problem Using a Genetic Algorithm

This subsection reviews the genetic algorithm proposed by Monoyios et al. [2009], to solve the problem of IA-RWA in transparent optical networks. The objective of the genetic algorithm is to minimize the number of lightpaths blocked due to physical layer impairments.

Monoyios et al. [2009] do not refer to any previous work and no shortcomings of previous work are mentioned.

Monoyios et al. [2009] model the IA-RWA in transparent optical networks, as a Multi-objective Optimization (MOO) problem in order to take into account various physical layer impairments. A MOO problem mainly involves the optimization of one or more objective functions subject to certain constraints. In a MOO problem it is not clearly possible to obtain a single solution that can optimize every objective function. Therefore, the authors state that a tentative solution called Pareto-optimal solution is found, which reasonably optimizes each of the objective functions, such that there exists no other better solution that can improve a particular objective function without worsening others.

The authors use a Genetic algorithm to solve the IA-RWA MOO problem. As a preprocessing step, k-shortest paths are computed for every source destination pair in the given network topology. A chromosome in molecular Biology, is treated as a structured collection of genes (hereditary information). In this problem every chromosome represents a potential RWA solution for the entire set of lightpath requests. Every gene inside a chromosome represents one of the k-shortest paths of every source destination pair for which lightpaths are to be established. An initial population of such chromosomes is created. The fitness of a chromosome (which is the fitness of that RWA solution) is evaluated using a fitness function that is based on the average cost of all the genes present in that chromosome. Three different types of costs are assigned to each of the genes in the chromosome which are namely the length of the k-shortest path represented by the gene, the number of hops which a gene shares in common with others and finally the number of fiber links that a gene shares with other genes. The authors state that the length of the lightpath and the number of hops that lightpaths share in common directly affect most of the physical layer impairments. Therefore, by including these parameters in the gene cost, the authors have indirectly considered the effects of physical layer impairments while performing the RWA.

The three types of gene costs represent the different objective functions (in the MOO problem) to be optimized. A set of chromosomes from the initial population are selected based on their fitness values and are considered for the crossover process. After the crossover is done, an additional set of chromosomes (called off springs) are generated. The fitness values of these newly generated chromosomes are also calculated. Finally a new set of chromosomes are selected (based on their fitness values) from the existing and the newly generated chromosomes subject to a maximum population size. This crossover is repeated till a pareto-optimal solution is obtained for the IA-RWA MOO problem. As a mutation step, the chromosome with the worst fitness value is selected and one of its genes modified. This is done generally to prevent looping around the same solutions.

Monoyios et al. [2009] state that they compared the performance of a Single Objective Genetic algorithm, SOGA, (that represents a traditional RWA, without considering any impairments, the objective function being the number of wavelengths used) with their Multi-Objective Genetic algorithms namely MOGA1 (that considers the path length and the number of common hops as its objective functions) and MOGA2 (that considers the path length, the number of common hops and the number of wavelengths used as its objective functions). The authors state that they used the blocking ratio of lightpaths as their performance evaluation metric.

Monoyios et al. [2009] state that MOGA offers lesser blocking ratio of lightpaths compared to SOGA. Also, they observe that MOGA1 performs better than MOGA2. The authors are of the view that MOGA achieves a lesser blocking ratio at the cost of using a larger number of available wavelengths.

Monoyios et al. [2009] do not make any claims with respect to the contribution they have made.

Year	Authors	Title	Papers Referred to	Major Contribution
2009	Monoyios et al	On the use of multi-objective optimization algorithms for solving the impairment aware-rwa problem	None	Solves the IA-RWA problem in transparent networks using a Genetic Algorithm.

Table IV. Summary of papers reviewed in Subsection 3.2

3.3 Solving the Impairment-Aware Routing and Wavelength Assignment Problem Using Hyper-Heuristics

This subsection reviews two IA-RWA Hyper-Heuristics proposed by Keles et al. [2010a] and Keles et al. [2010b] respectively. The authors state that Hyper-Heuristics operate on the search space of the heuristics rather than on the search space of the solutions. A Hyper-heuristic can be considered as a combination of a number of individual heuristics to obtain an optimal solution. The objective of these two heuristics is slightly different from those of the others presented in section 3. These Hyper-Heuristics aim to establish lightpaths in such a way that the total Bit Error rate (BER) of all routed lightpaths is minimum.

3.3.1 *Solving the Static IA-RWA Problem Using a Tabu Search Based Hyper-Heuristic.* Keles et al. [2010a] propose a new Tabu search based Hyper-Heuristic to solve the IA-RWA problem. The Tabu Search Hyper-Heuristic (TSHH) is applied to the routing part of the RWA problem. The wavelength assignment is done using a regular first-fit strategy.

Keles et al. [2010a] refer to the previous work by Pavon-Marino et al. [2009] and Manousakis et al. [2009]. No shortcomings of previous work are mentioned.

The authors use the following individual heuristics to establish lightpath requests: The Shortest Path (SP) heuristic selects the route with the shortest link length between the source and destination nodes. The K-Shortest Path (KSP) heuristic first computes K shortest paths for a given (source, destination) pair and then selects one of them randomly. The Least Congested Path (LCP) heuristic selects the path with least congestion (which has the least number of used wavelengths). The Lowest BER Path (LBERP) heuristic selects the path with the lowest BER among the K-shortest paths for that (source,destination) pair. Finally, the Minimizing Highest BER (MinHBERP) heuristic selects the path with the minimum BER value among the K shortest paths.

TSHH proposed by the authors proceeds as follows: Every lightpath request is associated with an individual heuristic, that is used to route that particular lightpath. In this way, a one dimensional array of heuristics is generated, whose indices correspond to the lightpath requests to be established. After establishing the lightpaths using the assigned heuristics, the total BER of all the lightpaths is measured and recorded. A certain number of iterations of this entire sequence of steps is performed by randomly changing the heuristic assigned to one of the lightpath requests. If any of the solutions obtained in this way fail at the wavelength assignment stage, then they are recorded as infeasible and TSHH is prevented from visiting the same solution again. Finally after the iterations are over, the RWA solution with the least total BER value is selected.

Keles et al. [2010a] state that they compared the performance of TSHH (in terms of total BER of all lightpaths) with the individual heuristics namely SP, KSP, LCP, LBERP and MinHBERP. The authors state that they used twenty different randomly generated network topologies for the performance evaluation.

Keles et al. [2010a] state that the total BER value of TSHH is comparable to that of the other heuristics. The authors state that no single heuristic offers the lowest BER in all the network topologies. Hence, they are of the view that TSHH, which combines all the individual heuristics, provides a workable and reasonably good solution when different network topologies are considered collectively.

Keles et al. [2010a] claim that they are the first to apply a Hyper-Heuristic based approach to the static IA-RWA problem.

3.3.2 *Solving the Static IA-RWA Problem Using a Swarm Intelligence based Optimization Technique.* Keles et al. [2010b] propose a new Ant Colony Optimization (ACO) based Hyper-Heuristic (ACHH) to solve the IA-RWA problem. The authors refer to the previous work by Pavon-Marino et al. [2009] and Manousakis et al. [2009]. No shortcomings of previous work are mentioned.

ACO algorithms are used to solve problems in Computer Science by converting them into shortest path search problems. In ACO ants first find a source of food and while carrying the food back to their colonies secrete a chemical substance called pheromone along the path/route they take. The pheromone attracts other ants also to take the same path. The power of the pheromone to attract other ants depends on its intensity which evaporates with time. It is more likely that a path which is shorter in length will have a higher intensity of the pheromone, because it is reinforced quickly by the moving ants.

In the proposed Hyper-Heuristic (ACHH), simulated ants move over a topology, whose nodes represent individual heuristics. The authors use the following individual heuristics: The Shortest Path (SP) heuristic selects the route with the shortest link length between the source and destination nodes. The K-Shortest Path (KSP) first computes K shortest paths for a given (source, destination) pair and then selects one of them randomly. The Least Congested Path (LCP) heuristic selects the path with least congestion (which has the least number of used wavelengths). The Lowest BER Path (LBERP) heuristic selects the path with the lowest BER among the K-shortest paths for that (source,destination) pair. Finally, the Minimizing Highest BER (MinHBERP) heuristic selects the path with the minimum BER value among the K shortest paths.

In ACHH the network nodes are initialized with pheromone values and the ants start moving along the topology based on the pheromone trail values. Every move of an ant adds a heuristic to the solution, which is used to route the particular lightpath. So, the number of moves of each ant represents the total number of ligtpaths that are to be established. After all the simulated ants move and construct the solution, the total BER values of the corresponding lightpaths are measured and recorded. A certain number of iterations are repeated using different initializations of pheromone values. Finally, the solution that provides the lowest total BER is selected.

Keles et al. [2010b] state that they compared the performance of ACHH (in terms of the total BER of all established lightpaths) with the TSHH heuristic proposed by Keles et al. [2010a] and also with the individual heuristics used as part of ACHH (namely SP, KSP, LCP, LBERP and MinHBERP). The authors state that measured the total BER for twenty different randomly generated virtual network topologies (VTs).

Keles et al. [2010b] state that the experiments that they conducted indicate that ACHH gives the best performance for some of the VTs and a performance closely comparable to other individual heuristics in the remaining VTs. Keles et al. [2010b] are of the view that since no single heuristic gives the best performance in all the different types of network topologies, ACHH is a good alternative to use because it combines all the individual heuristics and provides a solution comparable to others in all cases.

Keles et al. [2010b] claim that they are the first to attempt an ACO based approach for the IA-RWA problem in transparent optical networks. The authors also claim that ACHH and TSHH outperform other single heuristics when the network resources (wavelengths per fiber) are limited.

Year	Authors	Title	Papers Referred to	Major Contribution
2010	Keles et al	Solving the physical impairment aware routing and wavelength assignment problem in optical wdm networks using a tabu search based hyper-heuristic approach	Pavon-Marino et al. 2009 and Manousakis et al. 2009	First paper to apply a Hyper-Heuristic based approach to the static IA-RWA problem in transparent optical networks.
2010	Keles et al	Ant based hyper heuristic for physical impairment aware routing and wavelength assignment	Pavon-Marino et al. 2009 and Manousakis et al. 2009	First paper to attempt an Ant Colony Optimization based approach for the static IA-RWA problem in transparent optical networks.

Table V. Summary of papers reviewed in Subsection 3.3

4. CONCLUDING COMMENTS

The survey reviewed ten important papers on Static Impairment-Aware RWA in optical WDM networks. The focus of this survey was on the heuristics presented in these papers. The heuristics were classified broadly into two categories (namely translucent and transparent), depending on whether optical signal regenerators were used in the network. A majority of the papers reviewed fall into the transparent category (7 papers). Blocking ratio of lightpaths was used as the performance evaluation metric in all the heuristics reviewed.

Ezzahdi et al. [2006] appear to be the first researchers to propose an IA-RWA heuristic in Optical WDM networks. The work of Ezzahdi et al. [2006] falls specifically in the category of translucent networks and has been cited widely by papers belonging to both translucent and transparent category. Of the ten papers reviewed in this survey, four of them dealt with Integer Linear Programming (ILP) based IA-RWA heuristics namely [Manousakis et al. 2009], [Pavon-Marino et al. 2009], [Azodolmolky et al. 2010] and [Garcia-Manrubia et al. 2011].

It is interesting to note that most of the static IA-RWA heuristics in the literature were new proposals. Only a few of them were enhancements of earlier works. Researchers in four of the ten papers reviewed in this survey, compared their works with previously proposed heuristics, namely Pavon-Marino et al. [2009], Azodolmolky et al. [2010], Sengezer and Karasan [2010] and Garcia-Manrubia et al. [2011]. Whereas, the remaining six papers did not make any comparisons to other heuristics from the literature, with [Ezzahdi et al. 2006] being an exception, since it happens to be the very first work on IA-RWA in optical WDM networks.

In spite of the differences in the IA-RWA heuristic approaches, it can be observed that a majority of the papers used the K-shortest path algorithm to compute the set of candidate routes to be assigned to lightpaths during the RWA phase. Evaluation of the physical layer impairments is fundamental to any IA-RWA heuristic and a majority of the papers reviewed in this survey used the same analytical model to measure the effects of physical impairments.

The research papers reviewed in this survey do not give a specific direction for future research. However, it can be concluded that there is a need for a benchmark against which various IA-RWA heuristics can be compared. Such a benchmark would enable all future IA-RWA heuristics to be compared with each other and also with some of the milestone heuristics proposed in the literature. This will lead to a wider acceptability of the proposed heuristics in the research community.

A summary of the papers reviewed in this survey is presented in Table VI.

Year	Authors	Title	Papers Referred to	Major Contribution
2006	Ezzahdi et al	LERP: a quality of transmission dependent heuristic for routing and wavelength assignment in hybrid wdm networks	None	First paper to present an IA-RWA heuristic in translucent optical Networks.
2009	Bakri et al	Static lightpath establishment with transmission impairments consideration in wdm all-optical networks	None	First paper to consider the impact of four major physical impairments in an IA-RWA heuristic for transparent networks.
2009	Manousakis et al	Offline impairment-aware routing and wavelength assignment algorithms in translucent wdm optical networks	Ezzahdi et al. 2006 and Christodoulopoulos et al. 2009	A new Static IA-RWA heuristic for translucent networks.
2009	Monoyios et al	On the use of multi-objective optimization algorithms for solving the impairment aware-rwa problem	None	Solves the IA-RWA problem in transparent networks using a Genetic Algorithm.
2009	Pavon-Marino et al	Offline impairment aware rwa algorithms for cross-layer planning of optical networks	Markidis et al. 2007	Proposes two new IA-RWA heuristics in transparent networks.
2010	Azodolmolky et al	A novel offline physical layer impairments aware rwa algorithm with dedicated path protection consideration	Ezzahdi et al. 2006 and Manousakis et al. 2009	Enhances the heuristic proposed by Ezzahdi et al. [2006]. Offers lesser blocking ratio compared to Ezzahdi et al. 2006.
2010	Keles et al	Solving the physical impairment aware routing and wavelength assignment problem in optical wdm networks using a tabu search based hyper-heuristic approach	Pavon-Marino et al. 2009 and Manousakis et al. 2009	First paper to apply a Hyper-Heuristic based approach to the static IA-RWA problem in transparent optical networks.
2010	Keles et al	Ant based hyper heuristic for physical impairment aware routing and wavelength assignment	Pavon-Marino et al. 2009 and Manousakis et al. 2009	First paper to attempt an Ant Colony Optimization based approach for the static IA-RWA problem in transparent optical networks.
2010	Sengezer and Karasan	Static lightpath establishment in multilayer traffic engineering under physical layer impairments	Ezzahdi et al. 2006, Azodolmolky et al. 2009 and Monoyios et al. 2009	Proposes a new IA-RWA heuristic for transparent networks. Outperforms the heuristic proposed by Azodolmolky et al. [2009].
2011	Garcia-Manrubia et al	Offline impairment-aware rwa and regenerator placement in translucent optical networks	Ezzahdi et al. 2006 and Manousakis et al. 2009	Proposes two new heuristics separately considering Linear and Non-Linear impairments. The proposed heuristics offer better performance compared to Ezzahdi et al. 2006 and Manousakis et al. 2009.

Table VI. Summary of papers reviewed in this survey

5. ACKNOWLEDGEMENTS

I am extremely grateful to Dr. Richard A. Frost for his invaluable guidance and constructive suggestions throughout the conduct of the survey. I would also like to sincerely thank my supervisors, Dr. Subir Bandyopadhyay and Dr. Arunita Jaekel, for helping me to finalize the survey topic.

6. ANNOTATIONS

6.1 Azodolmolky et al. 2010

Citation: Azodolmolky, S., Klinkowski, M., Pointurier, Y., Angelou, M., Careglio, D., Sole-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 researchers/authors addressed. In transparent or all-optical networks the signal remains in the optical domain without any optical-to-electronic-to-optical conversion (OEO) at any of the intermediate nodes in the network. Transparent or all-optical networks offer a cost effective solution since OEO conversion is costly. As the optical signal propagates along a lightpath its quality of transmission (QOT) is degraded due to a number of physical layer impairments. As a result, the signal is received with unacceptable quality level at the destination node and such lightpaths are rejected. Since in transparent networks the signal always remains in the optical domain, devices such as 3R regenerators are not used to restore the QOT of the signal. Azodolmolky et al. [2010] address the problem of Impairment-Aware Routing and Wavelength Assignment (IA-RWA) in transparent or all-optical networks. Since this problem does not involve the placement or assignment of regenerators, the main objective is to minimize the number of connection/lightpath requests that are rejected due to unacceptable QOT.

Previous work by others referred to by the authors. The authors refer to the previous work by Ezzahdi et al. [2006] and Manousakis et al. [2009].

Shortcomings of previous work. No shortcomings of previous work are mentioned.

The new idea, algorithm, architecture, protocol, etc. Azodolmolky et al. [2010] enhance the heuristic approach proposed by Ezzahdi et al. [2006] and also enhance an ILP based RWA algorithm from the literature by adding impairment aware constraints (enhanced ILP is called as ILP-RWA-LU in the paper). Finally the authors propose a new IA-RWA heuristic for transparent or all-optical networks. Additionally, the authors also propose slightly modified versions of their heuristics to consider the dedicated path protection requirement for certain lightpath requests.

The IA-RWA heuristic proposed by Ezzahdi et al. [2006] (called LERP) proceeds in two phases namely the RWA phase and the QOT Test phase. The functionality of the RWA phase is just to assign a tentative route and a wavelength for each lightpath request. The lightpaths established in the RWA phase are then fed to the QOT-Test phase which handles the functionality of evaluation of impairments for the lightpaths and proceeds with the placement of regenerators accordingly.

Azodolmolky et al. [2010] extend the RWA phase of the LERP heuristic (the extended version is called RS-RWA-Q) to include the evaluation of physical layer impairments in it. In RS-RWA-Q heuristic k-shortest paths are computed for each pair of (source, destination) nodes and the lightpath requests are ordered randomly. Then a sequential RWA is performed to establish the connection requests. After the RWA is done, the Q-factor values of all the established lightpaths are measured. A lightpath with an inadmissible Q-factor value is considered as rejected. A lightpath could also be rejected during the RWA due to the unavailability of a required wavelength. The RWA and Q-factor evaluation stages are repeated for different random orderings of the lightpath requests and finally the RWA solution which offers the lowest number of rejected lightpaths is selected. The authors also add a dedicated path protection requirement to the RS-RWA-Q heuristic by putting the protected lightpath requests before others while ordering them in the first step.

The authors finally propose a new IA-RWA heuristic (called "Rahyab") for transparent optical networks. As a preprocessing step, the shortest paths are computed for each source destination pair and then the lightpath requests are arranged in the decreasing order of the length of the shortest path between the corresponding source and destination nodes. A layered network graph is created using the given network topology. This layered network graph contains the entire topology replicated w times in the form of layers, where w represents the maximum number of available wavelengths on all fiber links. For each lightpath request candidate routes are established in each of these w wavelength layers. Then the authors evaluate the Q factors values of each of these candidate paths (Qp) using a customized Q-factor evaluation tool. The combined Q-factor (say Qc) of all the already established lightpaths is also computed. Finally, the candidate lightpath with the highest non-negative (Qc - Qp) value is considered as established and the network topology is updated to reflect the change. If the algorithm is unable to establish a lightpath request, then it is considered as rejected. Azodolmolky et al. [2010] have also proposed a slightly modified version of their Rahyab heuristic to include the dedicated path protection requirement for certain lightpath requests.

Experiments and/or analysis conducted. Azodolmolky et al. [2010] state that they compared the performance of their enhanced heuristic (RS-RWA-Q) with the plain RS-RWA proposed by Ezzahdi et al. [2006]. The authors also state that they compared the performance of their new heuristic (Rahyab) with the RS-RWA-Q and ILP-RWA-LU enhancements.

Results that the authors claim to have achieved. The authors state that they used blocking rate of lightpath demands as their fundamental performance evaluation metric. The blocking rates (of all the heuristics), for different values of network loads and maximum number of wavelength channels per fiber link, were represented graphically.

Claims made by the authors. Azodolmolky et al. [2010] claim that their enhanced RS-RWA-Q heuristic offers 35% lesser blocking rate (on an average for different loads) compared to the RS-RWA proposed by Ezzahdi et al. [2006]. They also claim that their Rahyab heuristic performs even better than their enhancements.

Citations to the paper by other researchers. None

6.2 Bakri et al. 2009

Citation: Bakri, M., Koubaa, M., Menif, M., and Ouerda, I. 2009. Static lightpath establishment with transmission impairments consideration in wdm all-optical networks. In *Proceedings of 7th International Workshop on Design of Reliable Communication Networks, 2009. DRCN 2009.* 251-258.

The problem which the researchers/authors addressed. In transparent or all-optical networks the signal remains in the optical domain without any optical-to-electronic-to-optical conversion (OEO) at any of the intermediate nodes in the network. Transparent or all-optical networks offer a cost effective solution since OEO conversion is costly. Most of the previous studies on traditional RWA (in transparent networks) do not consider the effects of physical layer impairments on the signal quality. As a result, every established lightpath is assumed to be feasible. But in a practical sense, only those lightpaths with an acceptable level of Quality of transmission (in terms of its Bit Error rate) can be considered as feasible. Bakri et al. [2009] address the problem of Static lightpath establishment in transparent optical networks with physical layer impairments consideration.

Previous work by others referred to by the authors. The authors do not refer to any previous work.

Shortcomings of previous work. No Shortcomings of previous work are mentioned.

The new idea, algorithm, architecture, protocol, etc. Bakri et al. [2009] propose three new Impairment-Aware Routing and Wavelength Assignment (IA-RWA) algorithms (given a set of static lightpath demands). In all the three algorithms, the authors use their own analytical model to evaluate the Q-factor of the established lightpaths.

The first algorithm is called QPSA (Quality Path Selection Algorithm). As a preprocessing step, K-shortest paths are computed for every (source, destination) pair in the given network topology. There could be multiple lightpaths that need to be setup for the same (source, destination) pair. Hence, it is important that the number of available wavelengths on the selected route/path should be greater than or equal to the number of lightpaths requested between the pair of nodes. Each (source, destination) pair, for which lightpath(s) are to be established, the set of corresponding K-shortest paths are scanned sequentially and the Q-factor values of every (path, wavelength) combination are computed. The first route/path, that offers the required quality of transmission (QOT) and the required number of wavelengths, is selected to establish the lightpath and the network status is updated accordingly. If a path with the required QOT is not found, then the lightpath request is considered as rejected.

The second algorithm called WQPSA (Worst Quality Path Selection Algorithm) is an extension of QPSA. In WQPSA, instead of selecting the first path that offers the required QOT, a set of admissible paths, that offer the required QOT, is computed first. From this set, the (path, wavelength) combinations whose Q-factor values are close to the threshold (i.e. with higher or worst Q-factor values) are given priority while making the selection. This criteria mainly helps in minimizing the number of rejected lightpath requests because those (path, wavelength) combinations with lesser Q-factor values are preserved for further requests.

The third algorithm called SWQPSA (Shortest Worst Quality Path Selection Algorithm), is a further extension to the WQPSA algorithm. This algorithm proceeds in 3 phases, in which phase 1 and phase 2 correspond to the QPSA and WQPSA algorithms respectively. At the end of phase 2, unlike in the case of WQPSA where the network status is updated with the established lightpath, in SWQPSA the lightpaths are only assumed to be established and among these lightpaths the one which has the shortest path only is actually treated as established. The remaining lightpaths are again fed back to phase 1 as lightpath requests. This process is repeated until all the lightpaths are established. The main purpose of following this process is to establish first, those lightpaths which consume the minimum number of network resources, so that it finally leads to a minimum number of blocked lightpath requests.

Experiments and/or analysis conducted. Bakri et al. [2009] state that they compared the performances of QPSA, WQPSA and SWQPSA with that of a plain RWA (which does not consider impairments) referred to as SPSA (Shortest path Selection Algorithm) in the paper. The authors state that they have used the lightpath rejection ratio as their fundamental performance evaluation metric.

Results that the authors claim to have achieved. The authors state that the experiments that they conducted clearly indicate that the plain RWA (SPSA) achieves much lesser lightpath rejection ratio compared to their proposed algorithms. They are of the view that this trend emphasizes the importance of considering physical layer impairments while performing RWA. Also, they state that SWQPSA is the worst performing among the three IA-RWA algorithms.

Claims made by the authors. Bakri et al. [2009] claim that they are the first to consider the simultaneous impact of four important physical layer impairments (namely Chromatic Dispersion, Polarization Mode Dispersion, Optical Signal to Noise Ratio and Nonlinear Phase Shift) while performing RWA in transparent optical networks.

Citations to the paper by other researchers. None

6.3 Ezzahdi et al. 2006

Citation: Ezzahdi, M., Al Zahr, S., Koubaa, M., Puech, N., and Gagnaire, M. 2006. Lerp: a quality of transmission dependent heuristic for routing and wavelength assignment in hybrid wdm networks. In *Proceedings of 15th International Conference on Computer Communications and Networks, 2006. ICCCN 2006.* 125-136.

The problem which the researchers/authors addressed. Research so far on Routing and Wavelength Assignment in Optical WDM networks does not consider the feasibility of the established lightpaths in terms of its Bit Error Rate (BER) at the destination node. A number of Physical layer impairments in the fiber links cause degradation of the optical signal as a result of which BER of the lightpath at destination node goes above the prescribed threshold limit. Optical 3R regenerators are placed at the intermediate nodes along the lightpath to keep the BER value within the threshold limit. Ezzahdi et al. [2006] address the problem of lightpath establishment with regenerator placement under a static traffic scenario. Since every regeneration involves Optical to Electronic to Optical conversion (OEO), it adds to the network cost and therefore the primary objective is to minimize the number of regenerators to be placed.

Previous work by others referred to by the authors. [Ezzahdi et al. 2006] is one of the earliest papers to address the problem of Static Impairment-Aware Routing and Wavelength Assignment and therefore the authors do not refer to any specific previous work.

Shortcomings of previous work. No Shortcomings of previous work are mentioned.

The new idea, algorithm, architecture, protocol, etc. Ezzahdi et al. [2006] propose a new Static Impairment-Aware Routing and Wavelength Assignment (IA-RWA) algorithm called LERP (Lightpath Establishment with Regenerator placement) that is an improvement over a previous algorithm from the literature which is referred to as sLERP (Simple LERP) in this paper. sLERP algorithm proceeds in 2 phases namely the RWA phase and the QOT-Test phase.

The RWA phase of sLERP is only responsible for assigning a route and a wavelength to the connection requests between various (source, destination) pairs. The effect of physical layer impairments is not yet considered in this phase. The RWA phase intially uses a sequential RWA algorithm, that is based on the k-shortest path concept, to establish the lightpaths. Some of the connection requests could be rejected or blocked due to unavailability of wavelength channels. The lightpaths established using the sequential RWA algorithm are therefore rerouted using a Random Search (RS) based algorithm in order to minimize the number of rejected lightpath requests.

The QOT-Test Phase of sLERP deals with the effect of physical layer impairments on the feasibility of a lightpath. For each of the lightpaths obtained from the RWA phase, the Q-factor value is evaluated at each of the intermediate nodes along the route of the lightpath. If the Q-factor at any particular node i is found to be below the prescribed threshold limit for the network then a regenerator is placed at the previous node i-1. This is continued till the destination node is reached.

In LERP algorithm the RWA phase is exactly same as that of sLERP. The improvement is made in the QOT-Test phase. In the QOT-Test phase of LERP when the Q-factor of a lightpath at any of the intermediate nodes (say i) goes below the threshold, a regenerator is placed at the previous node i-1 and the remaining portion of the lightpath (i,destination) is put into a new traffic matrix. The lightpath (source, i-1) is recorded as established. Once the Q-factor evaluation is done for all the lightpaths in a similar way, the newly obtained traffic matrix is again fed back to the RWA phase. This loop of RWA and QOT-Test phases is repeated till all the lightpaths meet the Q-factor requirements. The basic objective of creating a new traffic matrix and sending it back to the RWA phase is to try to establish a route for a lightpath that uses the least number of regenerator nodes.

Experiments and/or analysis conducted. Ezzahdi et al. [2006] state that they have compared the performance of LERP and sLERP algorithms in terms of the number of rejected connection requests and the number of regenerator nodes used.

Results that the authors claim to have achieved. Ezzahdi et al. [2006] state that the experiments that they conducted clearly indicate that the LERP algorithm achieves lesser number of rejected lightpath requests and regenerators when compared to sLERP. The authors also state that LERP and sLERP algorithms achieve similar performance for higher number of wavelength channels in the fiber links.

Claims made by the authors. Ezzahdi et al. [2006] claim that their approach is unique because it takes into account the simultaneous impact of four major physical layer impairments namely Chromatic Dispersion (CD), Polarization Mode Dispersion (PMD), Amplified Spontaneous Emission (ASE) and Non-Linear Phase Shift, while evaluating the Q-factor of the lightpaths.

Citations to the paper by other researchers. Manousakis et al. [2009]; Azodolmolky et al. [2010]; Sengezer and Karasan [2010]; Garcia-Manrubia et al. [2011].

6.4 Garcia-Manrubia et al. 2011

Citation: Garcia-Manrubia, B., Pavon-Marino, P., Aparicio-Pardo, R., Klinkowski, M., and Careglio, D. 2011. Offline impairment-aware rwa and regenerator placement in translucent optical networks. *Journal of Lightwave Technology 29*, 3, 265-277.

The problem which the researchers/authors addressed. In Optical networks the signal quality is degraded due to a number of physical layer impairments as a result of which the Bit Error rate (BER) of the signal becomes inadmissible upon reaching the destination node. Physical layer impairments are classified broadly into two categories namely Linear and Non-Linear. Linear impairments are those that affect the same lightpath which generated them. Non-Linear impairments are those that are generated by other existing lightpaths in the network and affect a particular lightpath. Optical 3R regenerators are used along the route of the lightpath to restore the strength of the signal so that its BER is maintained within the threshold limit. Garcia-Manrubia et al. [2011] address the problem of Impairment-Aware Routing and Wavelength Assignment with regenerator placement (IA-RWA-RP) under a static traffic scenario separately considering the impact of linear and non-linear physical layer impairments.

Previous work by others referred to by the authors. The authors refer to previous work by Ezzahdi et al. [2006] and Manousakis et al. [2009].

Shortcomings of previous work. Garcia-Manrubia et al. [2011] state that the three phase heuristic proposed by Manousakis et al. [2009] is not able to effectively minimize the number of blocked connection requests.

The new idea, algorithm, architecture, protocol, etc. Garcia-Manrubia et al. [2011] formulate an Integer Linear Programming formulation (ILP) for the Linear IA-RWA-RP problem (that considers linear impairments only) in order to obtain the optimal solution. The authors also propose an ILP based algorithm, called LS (Lightpath Segmentation) Algorithm, to solve the Linear IA-RWA-RP problem. LS algorithm starts off by constructing a set of candidate lightpaths for every (source,destination) pair in the network. This set is further divided into two subsets based on whether a lightpath needs a regenerator or not. Then the algorithm iterates through the subset containing those lightpaths that require regenerators and splits each of them into semilightpaths (semilightpath is a portion of a bigger lightpath that does not need regenerators). There can be potentially a number of ways of splitting a non-transparent lightpath into semilightpath segments and therefore a set of candidate segmentations are created for every such lightpath. Finally, The two subsets and the generated segmentation sets are given as inputs to an Integer Linear Programming(ILP) formulation that solves the Routing and Wavelength Assignment problem where the objective function is to minimize the number of regenerators used and the number of blocked connection requests.

Garcia-Manrubia et al. [2011] also propose a Three Step heuristic for the linear IA-RWA-RP problem in larger network scenarios. The first step only considers the routing part of lightpaths. Routes with minimum number of intermediate hops are chosen to establish the lightpaths. The second step involves wavelength assignment for the routes setup in the first step. During this step if the wavelength continuity constraint cannot be satisfied for a particular lightpath then 3R regenerators (used as wavelength converters) are placed accordingly. Finally in the third step the lightpaths from step 2 are evaluated for their Q-factor values. If the Q-factor for a certain lightpath goes below the prescribed threshold, then it is divided into semilightpath segments and regenerators are placed accordingly. The heuristic continues till all lightpaths are established.

For the Non-Linear IA-RWA-RP problem, Garcia-Manrubia et al. [2011] propose a heuristic called Iterative Regenerator Placement (IRP) that is an extension of the three step heuristic proposed for the linear case. The first two steps of the IRP heuristic are same as that of the linear heuristic, with one small difference in the wavelength assignment step. In the wavelength assignment stage though regenerators are placed (used as wavelength converters), the wavelengths are not assigned to the lightpaths. Finally in step 3, the lightpaths and regenerators placed in step 2 are given as an input to a Wavelength Assignment ILP that takes into account the effects of other lightpaths (non-linear impairments). The objective of this ILP is to minimize the noise variance caused by non-linear impairments. After the ILP ends, the Q-factor of every lightpath is tested and if all lightpaths have satisfactory Q-factor values then the heuristic ends. Otherwise, the lightpath is split into semilightpath segments and regenerators are placed accordingly.

Experiments and/or analysis conducted. The authors state that they performed separate evaluations for the Linear and Non-Linear IA-RWA-RP problems. For the linear case they compared their heuristics (the LS algorithm and the Three step heuristic) with the LERP heuristic proposed by Ezzahdi et al. [2006]. For the Non-Linear IA-RWA-RP case the authors compared their IRP heuristic with the PH-ILPmax algorithm proposed by Manousakis et al. [2009].

Results that the authors claim to have achieved. The authors have tabulated the regenerator cost values (for different values of wavelength channels per fiber and other network parameters) obtained for all the linear and non-linear heuristics considered for evaluation (namely LS algorithm, Three step heuristic, LERP algorithm, IRP heuristic and PH-ILPmax algorithm). The table also shows the percentage of lightpath blocking for the LERP and PH-ILPmax heuristics. Since the linear and non-linear heuristics proposed by Garcia-Manrubia et al. [2011] offer zero blocking of lightpaths, the table does not include any blocking values for them.

Claims made by the authors. Garcia-Manrubia et al. [2011] claim that they are the first to address the IA-RWA-RP problem by separately considering the impact of linear and non-linear physical layer impairments. The authors state that their Linear Heuristics (namely LS algorithm and Three Step Heuristic) clearly outperform the LERP heuristic proposed by Ezzahdi et al. [2006]. They also claim that their IRP non-linear heuristic outperforms the PH-ILPmax algorithm proposed by Manousakis et al. [2009].

Citations to the paper by other researchers. None

6.5 Keles et al. 2010a

Citation: Keles, A., Uyar, A., and Yayimli, A. 2010a. Solving the physical impairment aware routing and wavelength assignment problem in optical wdm networks using a tabu search based hyper-heuristic approach. *In Applications of Evolutionary Computation*, C. Di Chio, A. Brabazon, G. Di Caro, M. Ebner, M. Farooq, A. Fink, J. Grahl, G. Greenfield, P. Machado, M. ONeill, E. Tarantino, and N. Urquhart, Eds. Lecture Notes in Computer Science Series, vol. 6025. Springer Berlin / Heidelberg, 81-90.

The problem which the researchers/authors addressed. Optical networks are being used predominantly to meet increasing bandwidth requirements of internet users. This is mainly due to the fact that optical networks offer low Bit Error Rate (BER) and high bandwidth capabilities. Physical layer impairments degrade the quality of the optical signal as it propagates through a lightpath and as a result the BER of the lightpath increases. Most of the previous studies ignore the effects of these impairments and assume an ideal physical layer medium in which every established lightpath is assumed to be feasible. But in realtime optical networks, a lightpath with an unacceptable BER at the destination node cannot be used for communication. Keles et al. [2010a] address the RWA problem in transparent networks, with the primary objective of minimizing the total BER of all the routed lightpaths.

Previous work by others referred to by the authors. The authors refer to the previous work by Pavon-Marino et al. [2009] and Manousakis et al. [2009].

Shortcomings of previous work. No shortcomings of previous work are mentioned.

The new idea, algorithm, architecture, protocol, etc. Keles et al. [2010a] propose a new Tabu search based Hyper-Heuristic to solve the IA-RWA problem. The Tabu Search Hyper-Heuristic (TSHH) is applied to the routing part of the RWA problem. The wavelength assignment is done using a regular first-fit strategy. The authors state that Hyper-Heuristics operate on the search space of the heuristics rather than on the search space of solutions. A Hyper-heuristic can be considered as a combination of a number of individual heuristics to obtain an optimal solution.

The authors use the following individual heuristics to establish lightpath requests: The Shortest Path (SP) heuristic selects the route with the shortest link length between the source and destination nodes. The K-Shortest Path (KSP) heuristic first computes K shortest paths for a given (source, destination) pair and then selects one of them randomly. The Least Congested Path (LCP) heuristic selects the path with least congestion (which has the least number of used wavelengths). The Lowest BER Path (LBERP) heuristic selects the path with the lowest BER among the K-shortest paths for that (source,destination) pair. Finally, the Minimizing Highest BER (MinHBERP) heuristic selects the path with the minimum BER value among the K shortest paths.

TSHH proposed by the authors proceeds as follows: Every lightpath request is associated with an individual heuristic, that is used to route that particular lightpath. In this way, a one dimensional array of heuristics is generated, whose indices correspond to the lightpath requests to be established. After establishing the lightpaths using the assigned heuristics, the total BER of all the lightpaths is measured and recorded. A certain number of iterations of this entire sequence of steps is performed by randomly changing the heuristic assigned to one of the lightpath requests. If any of the solutions obtained in this way fail at the wavelength assignment stage, then they are recorded as infeasible and TSHH is prevented from visiting the same solution again. Finally after the iterations are over, the RWA solution with the least total BER value is selected.

Experiments and/or analysis conducted. Keles et al. [2010a] state that they compared the performance of TSHH (in terms of total BER of all lightpaths) with the individual heuristics namely SP, KSP, LCP, LBERP and MinHBERP. The authors state that they used twenty different randomly generated network topologies for the performance evaluation.

Results that the authors claim to have achieved. Keles et al. [2010a] state that the total BER value of TSHH is comparable to that of the other heuristics. The authors state that no single heuristic offers the lowest BER in all the network topologies. Hence, they are of the view that TSHH, which combines all the individual heuristics, provides a workable and reasonably good solution when different network topologies are considered collectively.

Claims made by the authors. The authors claim that they are the first to apply a Hyper-Heuristic based approach to the static IA-RWA problem.

Citations to the paper by other researchers. None

6.6 Keles et al. 2010b

Citation: Keles, A., Yayimli, A., and Uyar, A. 2010b. Ant based hyper heuristic for physical impairment aware routing and wavelength assignment. In *Proceedings of IEEE Sarnoff Symposium, 2010.* 1-5.

The problem which the researchers/authors addressed. Optical networks are being used predominantly to meet increasing bandwidth requirements of internet users. This is mainly due to the fact that optical networks offer low Bit Error Rate (BER) and high bandwidth capabilities. Physical layer impairments degrade the quality of the optical signal as it propagates through a lightpath and as a result the BER of the lightpath increases. Most of the previous studies ignore the effects of these impairments and assume an ideal physical layer medium in which every established lightpath is assumed to be feasible. But in realtime optical networks, a lightpath with an unacceptable BER at the destination node cannot be used for communication. Keles et al. [2010b] address the problem of Routing and Wavelength Assignment (RWA) in transparent optical networks, with the primary objective of minimizing the total BER of all the routed lightpaths.

Previous work by others referred to by the authors. The authors refer to the previous work by Pavon-Marino et al. [2009] and Manousakis et al. [2009].

Shortcomings of previous work. No shortcomings of previous work are mentioned.

The new idea, algorithm, architecture, protocol, etc. Keles et al. [2010b] propose a new Ant Colony Optimization (ACO) based Hyper-Heuristic (ACHH) to solve the IA-RWA problem. The authors state that a Hyper-Heuristic (HH) combines a number of individual heuristics to solve a given optimization problem. They state that unlike other heuristics, a HH operates on the search space of the individual heuristics rather than on the search space of the solutions for the problem.

ACO algorithms are used to solve problems in Computer Science by converting them into shortest path search problems. In ACO ants first find a source of food and while carrying the food back to their colonies secrete a chemical substance called pheromone along the path/route they take. The pheromone attracts other ants also to take the same path. The power of the pheromone to attract other ants depends on its intensity which evaporates with time. It is more likely that a path which is shorter in length will have a higher intensity of the pheromone, because it is reinforced quickly by the moving ants.

In the proposed Hyper-Heuristic (ACHH), simulated ants move over a topology, whose nodes represent individual heuristics. The authors use the following individual heuristics: The Shortest Path (SP) heuristic selects the route with the shortest link length between the source and destination nodes. The K-Shortest Path (KSP) first computes K shortest paths for a given (source, destination) pair and then selects one of them randomly. The Least Congested Path (LCP) heuristic selects the path with least congestion (which has the least number of used wavelengths). The Lowest BER Path (LBERP) heuristic selects the path with the lowest BER among the K-shortest paths for that (source,destination) pair. Finally, the Minimizing Highest BER (MinHBERP) heuristic selects the path with the minimum

BER value among the K shortest paths.

In ACHH the network nodes are initialized with pheromone values and the ants start moving along the topology based on the pheromone trail values. Every move of an ant adds a heuristic to the solution, which is used to route the particular lightpath. So, the number of moves of each ant represents the total number of ligtpaths that are to be established. After all the simulated ants move and construct the solution, the total BER values of the corresponding lightpaths are measured and recorded. A certain number of iterations are repeated using different initializations of pheromone values. Finally, the solution that provides the lowest total BER is selected.

Experiments and/or analysis conducted. Keles et al. [2010b] state that they compared the performance of ACHH (in terms of the total BER of all established lightpaths) with the TSHH heuristic proposed by Keles et al. [2010a] and also with the individual heuristics used as part of ACHH (namely SP, KSP, LCP, LBERP and MinHBERP). The authors state that measured the total BER for twenty different randomly generated virtual network topologies (VTs).

Results that the authors claim to have achieved. The authors state that the experiments that they conducted indicate that ACHH gives the best performance for some of the VTs and a performance closely comparable to other individual heuristics in the remaining VTs. Keles et al. [2010b] are of the view that since no single heuristic gives the best performance in all the different types of network topologies, ACHH is a good alternative to use because it combines all the individual heuristics and provides a solution comparable to others in all cases.

Claims made by the authors. Keles et al. [2010b] claim that they are the first to attempt an ACO based approach for the IA-RWA problem in transparent optical networks. The authors also claim that ACHH and TSHH outperform other single heuristics when the network resources (wavelengths per fiber) are limited.

Citations to the paper by other researchers. None

6.7 Manousakis et al. 2009

Citation: Manousakis, K., Christodoulopoulos, K., Kamitsas, E., Tomkos, I., and Varvarigos, E. A. 2009. Offline impairment-aware routing and wavelength assignment algorithms in translucent wdm optical networks. *Journal of Lightwave Technology 27*, 12, 1866-1877.

The problem which the researchers/authors addressed. The quality of an optical signal is degraded by physical layer impairments in the transmission fibers. Translucent optical networks use sparsely located 3R regenerators to periodically restore the strength of the optical signal before it falls below a certain threshold value. Given a physical network topology with a static traffic demand matrix, Manousakis et al. [2009] have addressed the problem of lightpath establishment in translucent optical networks considering Regenerator Placement and Regenerator Assignment as sub-problems. The fundamental objective is to minimize the overall network cost by reducing the number of used regenerator nodes.

Previous work by others referred to by the authors. The authors refer to previous work by Ezzahdi et al. [2006] and Christodoulopoulos et al. [2009].

Shortcomings of previous work. No Shortcomings of previous work are mentioned.

The new idea, algorithm, architecture, protocol, etc. The static Impairment-Aware lightpath establishment approach proposed by Manousakis et al. [2009] proceeds in three phases and considers two different types of input settings. One in which only a network topology and static traffic matrix are given and the algorithm is required to identify the regenerator sites and the number of regenerators to be placed at these sites, before proceeding with Routing and Wavelength Assignment. The second input setting assumes a given placement of regenerators and the objective is to select the specific regenerators to be used by the lightpaths. These two input settings are often referred to in the literature as Regenerator Placement and Regenerator Assignment respectively.

In the first phase of the algorithm the Q-factor values of all the lightpaths are computed. Based on the obtained Q-factor values the lightpaths are divided into transparent (that do not need regenerators) and non transparent (that need regenerators) categories. Lightpaths in the non-transparent category are split up into transparent lightpath segments by using regenerators. Manousakis et al. [2009] propose four Greedy technique based heuristics namely Virtual-Hop Shortest Path (VH), Physical-Hop Shortest path (PH), Physical length shortest path (PL) and Adjusted-Virtual-Hop (AVH), to solve the regenerator placement/assignment problem. The authors also propose an Integer Linear Programming (ILP) based algorithm for the regenerator placement/assignment problem. The ILP based algorithm internally uses each of these four Greedy heuristic techniques to find k shortest paths. The ILP uses three different objective functions namely the maximum number of regenerators among all nodes, the total number of regenerators used and the number of regeneration sites. Based on the objective function that is optimized the ILP is referred to as ILPmax, ILPsum and ILPsites respectively. At the end of this phase all the non-transparent lightpaths are converted into transparent connection requests by using regenerators.

The transparent lightpath requests from phase one are given as input to phase two which performs Impairment-Aware Routing and Wavelength assignment (IA-RWA). In this phase, the authors use the ILP based IA-RWA algorithm proposed by Christodoulopoulos et al. [2009]. Manousakis et al. [2009] state that any IA-RWA algorithm could be used in phase two, but they are of the view that the algorithm proposed by Christodoulopoulos et al. [2009] is particularly more suitable because it provides the advantage of incorporating the interference among the lightpaths (non-linear impairments). Some of the lightpath requests in phase two are blocked either due to unavailability of wavelengths or due to unacceptable quality of the lightpath. Finally in phase three the blocked connection requests from phase two are rerouted.

Experiments and/or analysis conducted. Manousakis et al. [2009] state that they conducted simulation experiments separately considering the regenerator placement and regenerator assignment scenarios. The authors state that they have used a combination of the ILP based algorithms (ILPmax, ILPsum and ILPsites) and the Greedy heuristics (VH, PH, PL and AVH) for performance evaluation. The performance evaluation metrics used by the authors include the blocking ratio of lightpath requests, total number of regenerators used, total number of regeneration sites and the number of wavelength channels used to establish lightpath requests.

Results that the authors claim to have achieved. The authors state that the experiments which they conducted indicate that for both regenerator placement and assignment problems, the PH heuristic and the PH-ILPmax algorithm exhibit relatively good performance in terms of the lightpath blocking ratio. But, they also state that these heuristics perform poorly in terms of the number of regenerators used in the case of regenerator placement problem. The authors also state that the PH-ILPmax combination consumes the least number of wavelengths in order to establish all the lightpath requests with zero blocking.

Claims made by the authors. Manousakis et al. [2009] do not make any claims with respect to the contribution that they have made.

Citations to the paper by other researchers. Azodolmolky et al. [2010]; Keles et al. [2010a]; Keles et al. [2010b]; Garcia-Manrubia et al. [2011].

6.8 Monoyios et al. 2009

Citation: Monoyios, D., Vlachos, K., Aggelou, M., and Tomkos, I. 2009. On the use of multi-objective optimization algorithms for solving the impairment aware-rwa problem. In *Proceedings of IEEE International Conference on Communications. ICC '09.* 1-6.

The problem which the researchers/authors addressed. Most of the previous studies on RWA assume an ideal physical layer medium and ignore the effects of physical layer impairments on the established lightpaths. As a result every established lightpath is considered to be feasible. But in a pratical scenario, the optical signal is degraded due to a number of physical layer impairments that accumulate as it propagates through the lightpath. Hence, it is important to consider the effects of these impairments while performing RWA. Monoyios et al. [2009] address the problem of Impairment-Aware Routing and Wavelength Assignment (IA-RWA) in transparent or all-optical networks assuming a static traffic scenario.

Previous work by others referred to by the authors. The authors do not refer to any previous work.

Shortcomings of previous work. No Shortcomings of previous work are mentioned.

The new idea, algorithm, architecture, protocol, etc. Monoyios et al. [2009] model the RWA in transparent optical networks, as a Multi-objective Optimization

(MOO) problem in order to take into account the physical layer impairments. A MOO problem mainly involves the optimization of one or more objective functions subject to certain constraints. In a MOO problem it is not clearly possible to obtain a single solution that can optimize every objective function. Therefore, the authors state that a tentative solution called Pareto-optimal solution is found, which reasonably optimizes each of the objective functions, such that there exists no other better solution that can improve a particular objective function without worsening others.

The authors use a Genetic algorithm to solve the IA-RWA MOO problem. As a preprocessing step, k-shortest paths are computed for every source destination pair in the given network topology. A chromosome in molecular Biology, is treated as a structured collection of genes (hereditary information). In this problem every chromosome represents a potential RWA solution for the entire set of lightpath requests. Every gene inside a chromosome represents one of the k-shortest paths of every source destination pair for which lightpaths are to be established. An initial population of such chromosomes is created. The fitness of a chromosome (which is the fitness of that RWA solution) is evaluated using a fitness function that is based on the average cost of all the genes present in that chromosome. Three different types of costs are assigned to each of the genes in the chromosome which are namely the length of the k-shortest path represented by the gene, the number of hops which a gene shares in common with others and finally the number of fiber links that a gene shares with other genes. The authors state that the length of the lightpath and the number of hops that lightpaths share in common directly affect most of the physical layer impairments. Therefore, by including these parameters in the gene cost, the authors have indirectly considered the effects of physical layer impairments while performing the RWA.

The three types of gene costs represent the different objective functions (in the MOO problem) to be optimized. A set of chromosomes from the initial population are selected based on their fitness values and are considered for the crossover process. After the crossover is done, an additional set of chromosomes (called off springs) are generated. The fitness values of these newly generated chromosomes are also calculated. Finally a new set of chromosomes are selected (based on their fitness values) from the existing and the newly generated chromosomes subject to a maximum population size. This crossover is repeated till a pareto-optimal solution is obtained for the IA-RWA MOO problem. As a mutation step, the chromosome with the worst fitness value is selected and one of its genes modified. This is done generally to prevent looping around the same solutions.

Experiments and/or analysis conducted. Monoyios et al. [2009] state that they compared the performance of a Single Objective Genetic algorithm, SOGA, (that represents a traditional RWA, without considering any impairments, the objective function being the number of wavelengths used) with their Multi-Objective Genetic algorithms namely MOGA1 (that considers the path length and the number of common hops as its objective functions) and MOGA2 (that considers the path length, the number of common hops and the number of wavelengths used as its objective functions). The authors state that they used the blocking ratio of lightpaths as their performance evaluation metric.

Results that the authors claim to have achieved. Monoyios et al. [2009] state that MOGA offers lesser blocking ratio of lightpaths compared to SOGA. Also, they observe that MOGA1 performs better than MOGA2. The authors are of the view that MOGA achieves a lesser blocking ratio at the cost of using a larger number of available wavelengths.

Claims made by the authors. The authors do not make any claims with respect to the contribution they have made.

Citations to the paper by other researchers. Sengezer and Karasan [2010].

6.9 Pavon-Marino et al. 2009

Citation: Pavon-Marino, P., Azodolmolky, S., Aparicio-Pardo, R., Garcia-Manrubia, B., Pointurier, Y., Angelou, M., Sole-Pareta, J., Garcia-Haro, J., and Tomkos, I. 2009. Offline impairment aware rwa algorithms for cross-layer planning of optical networks. *Journal of Lightwave Technology 27,* 12, 1763-1775.

The problem which the researchers/authors addressed. Optical networks are being used predominantly to meet increasing bandwidth requirements of internet users. This is mainly due to the fact that optical networks offer low Bit Error Rate (BER) and high bandwidth capabilities. The BER of an optical signal increases as it propagates through a lightpath due to the physical layer impairments at the optical fiber level. This problem is tackled using sparsely located optical signal regenerators (in translucent optical networks) at the intermediate nodes. But, every regeneration involves optical-to-electronic-to-optical conversion (OEO) which is very costly and tremendously increases the network cost.

On the other hand, in transparent networks the signal remains in the optical domain without the need for any OEO conversion and hence is a cost effective solution. But, the challenge in transparent optical networks is to use an efficient RWA scheme that takes into account the signal degradation due to physical layer impairments, so that every established lightpath meets the Quality of Transmission (QOT) requirements. Pavon-Marino et al. [2009] address the problem of Impairment-Aware Routing and Wavelength Assignment (IA-RWA) in transparent optical networks. The fundamental objective is to maximize the number of established lightpaths with an acceptable level of quality of transmission (in terms of its Q-factor).

Previous work by others referred to by the authors. The authors refer to the previous work by Markidis et al. [2007].

Shortcomings of previous work. The authors state that the IA-RWA approach proposed by Markidis et al. [2007] does not perform a collective wavelength assignment for all the lightpaths and hence does not consider the actual interference due to other lightpaths.

The new idea, algorithm, architecture, protocol, etc. Pavon-Marino et al. [2009] propose two new heuristic approaches to solve the IA-RWA problem in transparent optical networks namely: The Global Search Algorithm and the Sequential

Heuristic Approach.

The Global Search algorithm is an iterative search based algorithm that internally uses a fundamental Core Algorithm and three different Binary Integer Linear Programming (BILP) formulations to establish lightpaths with impairment-aware constraints. The Global Search algorithm proceeds in four phases. The first phase is a preprocessing stage in which two important parameters are computed namely: S_{IA}which is the set of (path, wavelength) pairs whose static Q-factor values (i.e. considering only linear impairments) are higher than the prescribed threshold (Q_{Th}). D is a two dimensional degradation matrix, that gives the degradation in the Q-factor of every lightpath due to others.

Phase 2 finds an initial RWA solution (from the set S_{IA}) using a BILP which does not use any impairment-aware constraints. The Q-factor values of the lightpaths in the obtained initial RWA solution are measured. In the obtained RWA solution, the number of lightpaths whose Q-factor values are above Q_{Th} is set as a lower bound (Llb) and the total number of lightpaths is set as an upper bound (Lub). The main idea of using these bounds is that, finally at the end of the algorithm the number of lightpaths which are successfully established (that meet the Q-factor threshold limit) should be between Llb and Lub.

Phases 3 and 4 are used to find an RWA solution with exactly a certain number of lightpaths (L) that meet the Q-factor threshold. The main objective of these phases is to maximize the value of L. Phase 3 uses a top-down approach in which it starts with L = Lub and gradually reduces its value till a solution is found. Phase 4 uses a bottom up approach in which it starts with L = Llb and increases the value of L selectively. The values of L visited during phase 3 are recorded and not repeated during phase 4.

The Core algorithm is fundamental to phases 3 and 4 of the Global Search algorithm. The Core algorithm is used to establish an exact number of lightpaths (say L, as prescribed by the phases), with the objective of maximizing the number of lightpaths among L that meet the QOT threshold. The Core algorithm starts by finding an initial solution using a BILP. This BILP does not take into account the non-linear or dynamic physical impairments and just tries to minimize the sum of static Q-factor values of the established lightpaths. This initial solution is refined in a certain number of fixed iterations. In each iteration, two sets of (path,wavelength) pairs are created. The first set contains those pairs that will remain active in the solution of the current iteration and the second set contains those pairs that will remain inactive. Each iteration makes a fixed number of changes to the solution of the earlier iteration. Each iteration uses a BILP in turn to establish the lightpaths. This final BILP takes into account the non-linear impairments as well.

The Sequential heuristic starts by finding the shortest path for every source destination pair in the topology, for which lightpaths are to be established. The product of the shortest path length and the number of lightpaths for each (source,destination) pair is computed. The (source, destination) pairs are arranged in the increasing and decreasing order of these product values. Then the set of ordered (source, destination) pairs is scanned sequentially and for each pair the required number of lightpaths are established in the following way: Initially the set S_{IA} is constructed, similar to the Global Search algorithm. A (path, wavelength) pair is removed from this set accordingly if this wavelength clashes with those of the existing lightpaths. Then they are ordered as per the increasing length of the path. The first 10 of these are selected and are added to the existing set of established lightpaths one at a time and the Q-factors of all the lightpaths are measured. If the worst Q-factor among all of them is less than the threshold then that particular (path, wavelength) pair is removed. Proceeding in this manner, the appropriate (path, wavelength) pairs are selected to meet the required lightpath requests. If no pair is found, then the corresponding lightpath request is blocked.

Experiments and/or analysis conducted. Pavon-Marino et al. [2009] state that they compared the performances of the Global Search algorithm, the Sequential Heuristic and the transparent IA-RWA variation of the LERP heuristic (referred to as sLERP) proposed by Ezzahdi et al. [2006]. The authors state that they used the blocking ratio of lightpath requests as their fundamental performance evaluation metric.

Results that the authors claim to have achieved. The authors state that the Global Search algorithm achieves the lowest blocking rate among all the heuristics (in different topologies and wavelength settings), followed by the Sequential heuristic and sLERP.

Claims made by the authors. The authors claim that their IA-RWA approaches clearly outperform the sLERP heuristic.

Citations to the paper by other researchers. Keles et al. [2010a]; Keles et al. [2010b].

6.10 Sengezer and Karasan 2010

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The problem which the researchers/authors addressed. Optical networks are being used predominantly to meet increasing bandwidth requirements of internet users. This is mainly due to the fact that optical networks offer low Bit Error Rate (BER) and high bandwidth capabilities. The BER of an optical signal increases as it propagates through a lightpath due to the physical layer impairments at the optical fiber level. This problem is tackled using sparsely located optical signal regenerators (in translucent optical networks) at the intermediate nodes. But, every regeneration involves optical-to-electronic-to-optical conversion (OEO) which is very costly and tremendously increases the network cost.

On the other hand, in transparent networks the signal remains in the optical domain without the need for any OEO conversion and hence is a cost effective solution. But, the challenge in transparent optical networks is to use an efficient RWA scheme that takes into account the signal degradation due to physical layer impairments so that every established lightpath meets the Quality of Transmission (QOT) requirements. Sengezer and Karasan [2010] address the problem of

Impairment-Aware RWA (IA-RWA) in transparent optical networks.

Previous work by others referred to by the authors. The authors refer to the previous work by Ezzahdi et al. [2006], Azodolmolky et al. [2009] and Monoyios et al. [2009].

Shortcomings of previous work. The authors state that the IA-RWA approach proposed by Azodolmolky et al. [2009] does not consider different orderings of the lightpath requests while performing the RWA. The authors are of the view that multiple orderings of the lightpath requests could improve the total number of established lightpaths that meet the QOT requirements.

The new idea, algorithm, architecture, protocol, etc. Sengezer and Karasan [2010] propose an IA-RWA Integer Linear Programming (ILP) formulation (to find the optimal solution) for small and medium sized networks followed by a new heuristic called "ROLE" (Reordered Lightpath Establishment Algorithm) for large size networks. ROLE heuristic proceeds in three phases namely: 1. Routing and Wavelength Assignment (RWA), 2. Rerouting and 3. Reordering. The fundamental objective of ROLE is to try different orderings of the lightpath requests using multiple RWA schemes to establish a maximum number of lightpaths that meet the QOT constraints. As a preprocessing step, the K-shortest paths are computed for every (source, destination) pair in the topology.

In the RWA phase three different types of routing schemes are used namely: the Shortest path First(SPF), the Shortest Widest Path First (SWPF) and the Widest Shortest Path First (WSPF). The width of the path here refers to the number of available or free wavelengths on the path. Also, three different wavelength assignment schemes are considered namely: the First Fit with BER constraint (FFB), the Minimum BER (MB) and the Maximum-Minimum BER (MMB). A combination of these routing and wavelength assignment schemes are tried to establish the lightpath requests. In addition to these schemes two exhaustive RWA schemes called the Exhaustive minimum BER (E-MB) and the Exhaustive Minimum-Maximum BER (E-MMB) are also proposed. These schemes are exhaustive in the sense that they do not stop if a particular wavelength is found. They try all possible wavelengths and select the one which offers the minimum BER for the established lightpath.

The Rerouting phase comes after the RWA is done. In this phase, attempts are made to reroute the blocked lightpaths from the RWA phase. Two classifications of the blocked lightpaths are made namely: The BER-blocked lightpaths (blocked due to BER constraints) and the Wavelength-blocked lightpaths (blocked due to unavailability of free wavelengths). The BER-blocked lightpaths are rerouted first followed by the Wavelength-blocked lightpaths.

The Reordering phase comes as a final step, in which the lightpaths that could not be established in the earlier two phases are marked and placed in the front of the lightpath request queue. The solution from the earlier phases is saved or recorded. This new sequence of lightpath requests are again fed to the RWA phase. This process is repeated until every lightpath request is established in some or the other iteration. Finally, the solution which offers the highest number of Q-feasible lightpaths is selected.

Experiments and/or analysis conducted. Sengezer and Karasan [2010] state that they measured the performance of different combinations of the routing schemes (SPF, SWPF, and WSPF) and the wavelength assignment schemes (FFB, MB, MMB, E-MB and E-MMB). The authors state that they also compared the performance of the ROLE heuristic with the POLIO-RWA heuristic proposed by Azodolmolky et al. [2009]. The authors state that they used, the percentage of established lightpaths, as their performance evaluation metric.

Results that the authors claim to have achieved. The authors state that the experiments they conducted indicate that the SWPF scheme gives the best performance among the routing schemes. They also state that MB and MMB wavelength assignment schemes offer similar performance better than the FFB scheme.

Claims made by the authors. The authors claim that the ROLE heuristic clearly outperforms the POLIO-RWA heuristic proposed by Azodolmolky et al. [2009].

Citations to the paper by other researchers. None.

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