A Survey on Static Routing Wavelength Assignment Considering Physical Layer Impairments in Wavelength Divison Multiplexing Optical Networks

Ganesh Santosh Akula
University of Windsor

Imagine a world of people who are connected through networks either they are far or close to each other and they could communicate in just "planks time"(that is believed to be the possible shortest duration) by paying less and obtaining great speed to communicate, this is just what the researchers are trying to obtain these days. One of the major problems facing optical networks is Routing and Wavelength Assignment (RWA) of optical signals taking into consideration the impairments caused by the physical layer. A regular RWA which does not consider impairments is often used to solve the RWA of optical signals but this approach could be improved. Various researchers have tried to solve regular RWA under physical impairments in order to improve or replace it. This survey is about their research.

Categories and Subject Descriptors: A.1.0 [**Lightpath Requests Establishment**]: Routing and Assigning Wavelength of requests considering Physical Layer Impairments.

General Terms: Routing and Wavelength Assignment, Regenerator Placement, Physical Layer Impairments.

Additional Key Words and Phrases: Static or Offline, Impairment Aware Routing and Wavelength Assignment, Physical Layer Impairments, Wavelength Division Multiplexing, Heuristic or ILP based approach, Optical Networks.

Contents

1. INTRODUCTION

This survey concerns research which attempts to solve the problem of effectively and efficiently routing lightpath signals or requests under physical impairments which cause degradation of signals when travelling in optical medium. If there are efficient ways to solve the problem of routing signals under physical impairments then it would enable more effective transmission of data over optical networks, with reduction in errors during transmission and makes the data more reliable and save cost by reducing the redundant transfer of data.

The published papers were identified using the following resources Google Schoolar, ACM digital library, Microsoft Academic Search and other sources available through the leddy library, various keywords were used to search.

Two of the research papers, namely Varvarigos et al. [2009], Zhang et al. [2009] were published in conference proceeding and eleven other papers were published in journals. These are: Christodoulopoulos et al. [2009], Manousakis et al. [2009], Pavon-Marino et al. [2009], Saradhi et al. [2009], Sengezer et al. [2010], Varvagiros et al. [2010], Zhai et al. [2010], Aparicio-Pardo et al. [2011], Katrinis et al. [2011], Sengezer et al. [2012], Sole et al. [2012],

The survey consists of a review of various techniques identified, final comments and annotations of the ten selected papers. Two main methods were identified to solve the question. Lastly there is a concluding part incorporating conclusion statements and annotations eventually.

Taking into consideration all the ten main papers identified it was discovered that most of the authors used both Integer Linear Programming (ILP) and Heuristic approach or either one of the two techniques that is Integer Linear Programming based approach or Heuristic based approach in order to route the lightpath requests under physical layer impairments.

2. APPROACHES

As stated earlier two distinct techniques have been to route lightpath requests. This survey focuses on these techniques and are classified into two categories one uses both ILP and heuristic based approach and other which uses either ILP or heuristic based approach to solve the problem.

2.1 Integer Linear Programming and Heuristic based approaches

Research papers that are considered in this section use the Integer Linear Programming (ILP) and the Heuristic based approaches to solve the problem. All of this research adopts an ILP and a Heuristic approach to route lightpath requests under physical layer impairments. A unique approach was proposed by Zhang et al. [2009] in the early years and is followed by other approaches by various authors which are either new, extension or alteration to an existing technique to improve the efficiency and provide cost effective solution to the problem considered.

2.1.1 *Integer Linear Programming and Greedy Heuristic approach.* Manousakis et al. [2009] propose this method to minimize blocking of lightpaths with effective placement of regenerators. The authors state that during transmission of an optical signal the existence of physical impairments in optical fibers block the connection requests from reaching the destination. There should be efficient algorithms to re-

route blocked connections by selective placement as well as selective use of minimum number of regenerators which re-shapes, re-amplify and re-time the signal.

The authors refer to previous work of Manousakis et.al [2009] and identify no shortcomings in the approach but point out the shortcomings in general taking the overall scenario and state that in the previous approaches proposed used regenerators at every node which do not provide a cost effective solution and is a huge drawback and few other approaches do not consider the impairment effect at all.

The authors state that a new impairment aware algorithm was designed and implemented for routing and wavelength assignment along with solving regenerator placement and assignment problem in translucent networks which places regenerators at selective sites along with the number of regenerators to be placed. The authors state that the placement and assigning of regenerators is considered as a virtual topology design problem which utilize various ILP and greedy heuristic algorithms to solve it and apart from that the approach also determines sequence of regenerators to be utilized by the connections having impairments and transform the non-transparent connection to transparent signal by terminating and regenerating the signal at the specified 3R intermediate node and minimize the number of blocked connections.

The authors state that in order to evaluate the performance of the proposed impairment aware RWA algorithm numerous simulation experiments were performed with the IA-RWA algorithm. Virtual topology algorithms were implemented in Matlab and LINDO API was used to solve ILP related problems in order to evaluate the feasibility of lightpath. The Q-factor estimator was used in the experiment. The link model has a NRZ-OOK modulation format, 10 Gbps transmission rates, 50 GHz channel spacing with span length equals to 80km with Geant-2 network topology with 34 nodes and 54 bidirectional links.

The authors state that when the blocking ratio is graphed against the number of available wavelengths and demands the PH-based algorithms shows a blocking probability ranging from 0.05 to 0.00 and required wavelengths ranging from 90 to 110 to reach zero blocking with the number of demands varying from 700 to 400. Moreover the PH-ILP sum of regenerator algorithm required 115wavelengths and 461 regenerators while the VP-ILP sum of regenerator required 135 and 430 regenerators to reach zero blocking. In addition, the execution time of the IA-RWA algorithm for translucent network requires about 3 hours in which application of IA-RWA algorithm used by transparent network in translucent network consumes most of the time and the remaining phases requires only few 10s of seconds.

The authors state that with the use of the Q factor, low complexity of the virtual topology design problem make the approach efficient for small and large scale heterogeneous mesh networks. Among various algorithms proposed for the virtual topology design problem the ILP formulation helps in reducing the maximum number of regenerators to be placed and among the heuristics proposed the physical Hop heuristic exhibit better performance and stable function in all cases.

This paper is cited by Aparicio-Pardo et al. [2011], and Sole et al. [2012].

2.1.2 *Binary Integer Linear Programming and Sequential Heuristic approach.* Pavon-Marino et al.[2009] propose this technique to minimize blocking of lightpaths and improve the efficiency by satisfying more number of lightpath requests.

The authors state that the quality of signal degrades due to physical layer impairment and if there are no regenerators there are chances of bit errors to be more which in turn weakens the signal strength. The authors state that there should be appropriate techniques which consider impairments during signal transmission and help in serving maximum number of connections

The authors do not refer to any previous work.

The authors state that an IA-RWA offline algorithmic approach is used which performs a cross layer optimization between the physical and network layers present and take into account the directly the dominant impairment effect and upper bound on the interference noise variance it can tolerate is calculated and it is used as constraint the interfering noise caused by other lightpaths and avoid heavy ILP formulations.

The authors state that the performance of the proposed cross layer optimization is evaluated through simulations, MATLAB, LINDO API to solve related LP problems, generic DTnet topology. The capacity of a wavelength assumed equals to 10Gbps and finally to evaluate the feasibility of lightpath physical layer evaluation module was developed.

The authors state that assuming 16 wavelengths and random 100 traffic matrix the proposed IA-RWA algorithm manages to serve all the traffic matric upto load equals 0.8 with zero physical and networking blocking. For load equals 2.05 and for wavelengths=35 the pure RWA algorithm has blocking equal to 10 percentage while the IA-RWA has blocking equal to 0 percentage and running time was about 20min.

The authors claim that the cross layer optimization minimizes the number of wavelength used in the network and also select lightpaths with acceptable quality of transmission. The proposed algorithm has better performance improvement when compared to typical RWA algorithm.

This paper is cited by Aparicio-Pardo et al. [2011].

2.1.3 *Noval Integer Linear Programming and Heuristic approach.* Zhang et al. [2009] propose this approach to provide efficacious and productive way of transferring data with less bit errors during transmission. The authors state that most of research done in designing and routing optical signals assumes that the medium in which the data is transferred passes without any error in bits. But in fact the situation of non-erroneous transfer of data may not really occur since there are chances that some physical impairment may be introduced by the optical fibers or other components utilized to route optical signals. The authors state that such impairments should be taken into consideration while designing and routing optical signal and there should be appropriate techniques to transfer data with the help of optical signals without any bit errors during transmission and look into providing an efficient and effective routing of optical signal.

The authors do not refer to any previous work. However, they do state that even though physical impairments are considered during transmission of optical signals, there is no assurance of a particular request being accepted in order to transmit data because the signal could possibly generate high bit error rate and requests could be rejected. Hence many optical signal requests can not be accepted because of chances that it could not keep up the quality of the signal due to impairments,

which makes the whole network inefficient to accept many source and destination requests. Therefore there should be techniques to convert the inefficient signal to efficient signal even though some cost is involved so that we can increase the overall network utilization up to its maximum capability.

The authors state that during transmission of an optical signal, impairments are caused by the optical fibers or components used in the optical network which in turn is responsible for bit errors. To overcome the problem of bit errors during transmission of optical signals the authors introduce a novel Integer Linear Programming (ILP) formulation for small networks and a heuristic approach for a large network which places minimum number of 3R regenerators (where each R= reshaping, R= retiming, R= reamplification) in an efficient and effective way with optical electrical optical conversion capability to accommodate all requests.

The authors state that in order to compare and evaluate the performance of the proposed methods the pacific bell network topology was used to test the network which has 15 nodes and 21 links with 32 wavelengths per fiber capability apart from that CPLEX was also used to solve the ILP formulation to generate an optimal solution. The simulation was performed on a machine with a Intel Pentium 1.70GHz CPU and 512 MB memory.

The authors state that for traffic matrix size upto 70 starting from 50 size, nearly 4 regeneration nodes were required for ILP formulation method and for heuristic method it was varying from five to seven and beyond 70 traffic matrix size, ILP could not generate solution. In case of the heuristic approach it generated a feasible solution as the traffic matrix size increases. The running time performance for ILP to generate solution was 1000 millisecond whereas for a heuristic to generate a solution it was taking a few milliseconds.

The authors claim that the results obtained from the experiments show that their heuristic algorithm outperforms the ILP optimal solution for various traffic matrices and showed better result and performance than the ILP optimal solution.

2.1.4 *Integer Linear Programming and Polynomial Time Heuristic approach.* Sengezer et al. [2010] proposed this method to provide adequate use of bandwidth allocated while preventing any bit errors during transmission of lightpath request. The authors state that there is problem in establishing static versions of lightpath requests which consider physical impairments in the optical layer which is the backbone of the lower layer in the multilayer architecture which consists of a Service layer, Electrical layer and Optical layer. The authors state that there is a need to formulate efficient algorithms in order to satisfy maximum lightpaths (requests) with minimum blocking and bit error rates of the established lightpaths and make efficient use of the bandwidth allocated for transmission of data.

The authors refer to previous work by Christodoulopoulos et al. [2009] and identify a few shortcomings of that work, and of work by other authors also in this field of research working on the same problem. The authors state that the existing method was not investigated in detail and there was only a basic comparison with other methods which do not consider impairments and no further study was done. The authors state that there are many other factors which influence a lightpath to satisfy a demand and must be taken into consideration and investigated further.

The authors propose an Integer Linear Programming (ILP) formulation for static

lightpath establishment which considers physical layer impairments. The idea behind the ILP formulation is to route as many lightpath demands by making use of the resources provided. In formulating the ILP the authors considered the aggregate effect of the physical impairments through which low Bit Error Rate is guaranteed which is below the acceptable threshold. A set of paths for each source-destination are generated and each request is routed through paths chosen and at every level a link capacity constraint is imposed. A physical impairment model is used to provide with upper limit of impairments a lightpath can handle when it is routed from the source, and the level at the receiver is monitored using a linear expression which represent the noise level due to ASE, Cross-talk and by the signal itself. The authors state that there is a drawback in the ILP formulation as the size of the network increases the solution time also increases exponentially, which makes it infeasible for a large size network. To overcome this drawback a polynomial time heuristic approach called ROLE (ReOrdered Lightpath Establishment Algorithm) was formulated taking into consideration large size networks the objective of the heuristic is to route as many requests as possible taking consideration of the Bit Error Rate constraint and not violating it. The authors formulated the ROLE heuristic in three phases first is Routing and Wavelength Assignment, rerouting and reordering. In Routing and Wavelength Assignment shortest path is selected along with an available wavelength and best combination is looked for a particular lightpath demand. After RWA rerouting is performed in order to improve the results of the RWA phase, which has a few lightpaths blocked due to no available wavelength or due to BER threshold. The algorithm first tries to route the BER blocked demands and then wavelength blocked demands so that minimum node cross talk is achieved. In case of reordering the authors state that all the unsatisfied lightpath requests are made to undergo RWA and rerouting until there are no unsatisfied lightpath demands.

The authors state that in order to evaluate the performance of the ROLE algorithm proposed, and to make comparison with other approaches as well as to compare with itself based on sorting techniques, a randomly generated physical topology each with 20 nodes having 25-40 bidirectional links (topology1, topology2, topology3, topology4) using three different wavelengths 4,8,16 and which has the required lightpath demands generated randomly sorted in either shortest lightpath demand, longest lightpath demand was utilized. Experiments were also carried out on realistic Deutsche Telekom network topology in order to make a valid comparison with other proposed procedures. The ILP algorithm proposed by the author was solved using ILOG CPLEX optimizer which uses branch and cut method was compared with ROLE for a very small network and performance was evaluated.

According to the authors experiments on ROLE algorithm with taking into consideration both shortest demand first and longer demand first on various topologies shows percentage of routed lightpaths is from 65 for topology1 to 87 for topology4.

The authors claim that the proposed ROLE algorithm performed 14 percentage better than the best heuristic algorithm present so far (POLIO-RWA) for the same problem, and is also guaranteed to provide optimum solutions for different sets of demands for different network sizes.

This paper is cited by Sengezer et al.[2012].

2.1.5 *Integer Linear Programming and 3-Step,Lightpath Segmentation Heuristic approach.* Aparicio-Pardo et al.[2011] propose this method to provide minimal interference of lightpaths, wavelength conversion in order to avoid huge capital expenditure. The authors state that physical layer impairments degrade the quality of optical signals during their transmission which cause the transmitted data not to be received correctly because of high bit error rate. There should be techniques which consider these physical impairments and avoid or minimize the lightpath blocking, interferences between lightpaths, and wavelength conversion and improving the quality of signal.

The authors state that the existing approach which considers nonlinear variation of impairment (caused due to neighboring lightpaths in the networks) minimizing the bit error rate by placing regenerators and routing the signal according to the demand still has some demands blocked due to deteriorating quality of transmission and performance. In addition the authors do not consider the linear impairments caused due to the same lightpath. Therefore the authors state that the problem needs to be solved by considering essential parameters which account for successful transmission of optical signal and also satisfying maximum demands (requests).

The authors propose an Integer Linear Programming model which considers physical layer linear impairments and which the authors claim to be a novel approach which was previously not done by any other researchers for a small or medium sized network. Apart from the ILP model the authors also propose a different heuristic approaches for a wide or large network which considers linear and nonlinear physical impairments individually. The authors state that the technique or idea behind Integer Linear Programming was for each lightpath demand a set of valid semilightpaths which are optical signal traversing a sequence of fibers without undergoing any signal regeneration is calculated these semilightpaths forms a reachability graph which describes the ability of the semilightpaths to reach from one node to another, to improve the strength of the signal minimum number of regenerators planned are placed in order to improve and minimize the number of lightpaths which are blocked. This technique works for a small or medium size network and not for wide or large network, a new technique was proposed for such networks which is a heuristic approach and named it as Lightpath Segmentation, 3- Step Heuristic. The authors state that in Light path segmentation each candidate light path is divided or segmented into number of semilightpaths if the quality of signal measured by linear QoT estimator is less than the threshold, the degradation is caused by the physical layer linear impairments. The signals are made transparent by placing regenerators on the nodes which requires signal regenerations reducing the number of blocked light path requests, the algorithm minimizes such regenerator placement on nodes requiring signal regeneration and maximizes the number of lightpath requests from source to required destination. Here in order to make the formulation simple not all the valid semilightpaths are considered only few are considered and restriction is imposed. The authors state that a second heuristic approach called 3-step heuristic was also proposed which considers linear physical impairments in a large sized network. In this approach the authors initially allocate all the lightpaths without taking into consideration physical impairment, then check

whether wavelength continuity is not satisfying and signal degradation is occurring if yes then place regenerators accordingly for wavelength conversion and improving the quality of the signal to avoid bit errors and also to minimize network blocking to allocates maximum number of lightpath requests. The authors propose another heuristic called Iterative Regenerator Placement (IRP) which considers nonlinear physical impairments and which uses nonlinear QoT estimator to evaluate the quality of lightpath or semilightpaths used. Initially all the lightpaths are routed and where the wavelength continuity is not satisfying wavelength converters are placed then an iterative regenerator placement is followed, through which semilightpaths approaching a particular nodes having worst Q factor has a regenerator placed on the node which has this as an outgoing semilightpath and along with it wavelength is also assigned this is an iterative process and continues until all the resulting semilightpaths have a valid Q factor along the signal.

The authors take into consideration three reference network topologies in order to study the technique or approach proposed these reference topologies are INTERNET, NSFNET and NOBEL-EU, for a medium size network which is INTERNET, NSFNET 8, 16 wavelengths were tested per fiber and 80 wavelengths were tested in case of NOBEL-EU. The authors utilize Q-Personick factor in order to represent linear and non-linear QoT estimation, which considers 17 dB as maximum threshold of the acceptable Q-factor, which is also used as reference to validate the quality of a semilightpath which has a maximum link length as 2688 Km. In order to test authors consider a network topology, three traffic loads matrix which are low, medium, high which has traffic load factor as 0.4, 0.7, 1, with certain wavelengths per fiber the maximum number of lightpath demands are calculated and later the effects of network link lengths on the regenerator equipment cost planned are tested.

The authors state that the heuristics LS and Three-Step algorithms provide similar optimal solution and in specific LS algorithm provided better solution compared to rest algorithms as it requires less number of regenerators to be placed along with also having minimum lightpath blocking capability when considering linear impairments. By observing the results of the three different algorithms which consider linear impairments only it can be said that small sized networks do not require regeneration equipment at all and it is topological dependent. Drawing attention towards the execution time for the proposed algorithms which takes into consideration linear impairments and comparing among it the authors state that it can be observed that three-step algorithm has execution time below 1 second and highest execution time was observed in the ILP formulation method but LS showed variation in the execution time, it was less than one second in Internet and NSFNET network topologies most of the cases of inputs provided and it increased with increase in network size. The authors also conducted what they claim to be exhaustive testing taking into consideration non-linear impairments using iterative routing placement algorithm and observed that it outperforms ILP which considers physical hops (PH-ILP) and also has a better execution time.

The authors claim that the non-linear IA-RWA-RP algorithm is the best, in both lightpath blocking and regenerator cost, compared to PH-ILP and whereas in linear IA-RWA-RP the LS and three-step heuristics provide optimal or close to optimal

solutions in all tests conducted. In addition, the three-step algorithm guarantee that no signal regeneration blocking is produced

This paper is cited by Sole et al.[2012].

2.1.6 *Integer Linear Programming and Heuristic approach.* Katrinis et al.[2011] propose this method to avoid give and take between cost of signal regeneration and effectiveness of the signal and improve the ability of optical signal reaching long distance. The authors state that the quality of a signal degrades as it propagates through the optical medium and there should be techniques which take into account impairments caused due to physical layer during transmission, ways to strengthen the signal quality, and methods to determine how many signals should be deployed in a network in order to avoid signal degradation. The authors also state that techniques developed should be of low cost with an ability of signals to reach long distances without compromising signal quality and avoid any tradeoff between effectiveness of signal and cost of signal regeneration.

The authors state certain drawback from the previous approaches proposed in the same area of problem and state that with the existing techniques there was clear tradeoff between the number of regenerators to be placed and the capacity of the WDM network. There was more concentration on routing aspects rather than design of the network which is the most important before routing any light path demand. The authors also state that the existing methods assumed that the distance covered by lightpath is a good approximation of signal quality degradation which is not necessarily true and further it holds good only for cases where there are limited number of hops and for networks exhibiting high homogeneity of optical equipment.

The authors state that a new Integer Linear Programme was formulated, which according to authors was not previously stated by others in the literature and they consider it to be a novel approach. The authors state that the main aim of their ILP formulation is to specify the capacity (which is the number of fibers), number of links (Edges) through which a candidate path travels, number of wavelength per fiber it supports and minimize the total cost occurring of the dimensioned (the optimization of the capacity put on deployed network) network.

The authors state that inorder to test the ILP formulation proposed, the ILOG CPLEX v.11.1.1 mathematical programming engine was used for solving the Integer Linear Program instances. Impairment models were used to evaluate the Bit Error Rate throughout the experiment. The hardware utilized during the experiment was Intel Xenon CPU 2.80 GHz Linux workstation, equipped with 2GB RAM. The network topology utilized was NSFNET comprising of 16 nodes and 48 physical links, in regards to input traffic requests a randomly generated traffic matrix with 70 nonzero source/destination pairs, with 344 wavelengths was used, apart from it noise figures of amplifiers which are modeled using a normal distributed random variable with certain standard deviation and step level was used for the purpose of evaluation of optical equipment configuration.

The authors state that for optical reach values from 500 to 1250km and low heterogeneity (variation in optical equipment) percentage of impaired lightpaths was from 0 to 2.5 percentage for network dimensioning in combination with length-based regeneration. As the degree of heterogeneity increased the percentage of impaired

lightpaths increased from 2.5 percentage to 14.6 percentage. For optical reach 1500 km and 1750 km the percentage of impaired paths went upto 21 percentage. The authors also state that 90 percentage of saving in regenerators with IA Regenerator placement approach was seen for optical reach which is 500 and for various heterogeneity levels and then for optical reach 1750 the impairment aware regenerator placement has 60 percentage saving in regenerators used. When considering the case of uncertainty of heterogeneous levels impairment aware regenerator placement has on average of 138-209 regenerators used on average, specific to heterogeneity level 5 the saving was 35 percentage on average and yielding 10 percentage impaired paths on average.

The authors claim that the results obtained from the experiments show their approach has better results than the previous approach which considers placing regenerators based on the length rather than based on the quality of signal and achieved less regeneration cost along with providing good signal quality.

2.1.7 *Mixed Integer Linear Programming and Tabu, Greedy Search Heuristic approach.* Sengezer et al. [2012] propose a method which allows information passing from one layers to another in a network. The authors state that there is a need for proper topology design through which we can obtain less or no wavelength conversion at all during transmission of an optical signal considering physical impairments along its path. There is a need for design or a approach in which sharing of information between various layers in the wavelength division multiplexing network is taken care of in order to attain blocking-free performance and best utilization of resources available.

The authors refer to work done by Varvarigos et.al [2009], Sengezer et.al [2010] and points out certain shortcomings from the previous approaches referred as well as other techniques which are used to solve the problem and state that in the previous approaches the solutions obtained was not traceable for moderate or large size networks as the whole problem was divided into sub problems and there should also be care taken during integration of solutions obtained at every phase and if there is a mistake then we would not obtain optimal solution at all. The authors also state that all the subproblems consider only one layer and omit other layers present and ignore sharing of information also during its transmission in an optical network and physical layer impairments are also ignored. A heuristic approach formulated provided solution but it was observed that excess utilization of wavelengths than used was possible and further does not provide the optimal solution.

The authors state that their approach is the first of its kind in the area to solve the problem. They introduce, what they claim to be, a novel multilayer virtual topology design approach in which both wavelength assignment and physical layer impairments are considered, and which involves interaction of control planes of multi-protocol label switching and wavelength division multiplexing layers during topology design and share information using topology information sharing strategy in which a wavelength routing node architecture was followed in physical layer model. The authors also propose two topology designs: a) Tabu search virtual topology design, and b) Greedy search virtual topology design in order to solve multilayer virtual topology design. Apart from this a mixed integer linear programming approach was made to provide a bench mark to evaluate the performance of

other approaches to the multi-layer VTD problem.

The authors state that in order to evaluate the performance of the VTD algorithms and information strategies with different traffic rates and patterns changing with time. A wide area network is utilized with NSFNET topology with 21 links and 14 nodes spread over four different time zones. Apart from this inorder to evaluate the topology design algorithms CPLEX 12.1 optimization problem solver was used.

The authors state that on conducting experiment with 15 percentage traffic magnitude with 21 links and 14 nodes MILP shows 31.9, GS-VTD shows 27.82, TS-VTD with out layer interaction shows 36.7 and TS-VTD with layer interaction shows 0.03 percentages of bandwidth blocking and for a whole day time period blocking ratio for a single-hour traffic demand was 3.19 percentage and for multi-hour traffic demand it was 2.40 percentage both having 100 percentage traffic intensity.

The authors claim that the proposed method solves the multi-layer logical topology design and LSP routing problems arising in MPLS layers, and routing and wavelength assignment problems in the wdm layers in an integrated approach that does not necessitate a single common control plane for both layers. The authors also state that MILP formulation approach does not generate good solutions and when taking into consideration heuristic approach Tabu search based algorithm can reduce the blocking ratio of the GS-VTD algorithm by 35 to 100 percentage.

2.1.8 *Summary.*

Year	Author	Title of Paper	Major Contribution
2009	Manousakis et al.	Offline Impairment-Aware Routing and Wavelength Assignment Algorithms in Translucent WDM Optical Networks	A novel integer linear programming and heuristic approach for routing and wavelength assignment along with solving regenerator placement.
2009	Pavon-Marino et al.	Offline Impairment Aware RWA Algorithms for Cross-Layer Planning of Optical Networks	An integer linear programming and heuristic approach which perform cross layer optimization serving maximum lightpath requests
2009	Zhang et al.	REPARE: Regenerator Placement and Routing Establishment in Translucent Networks	A novel Integer Linear Programming formulation and heuristic approach for placing regenerators.
2010	Sengezer et al.	Static Lightpath Establishment in Multilayer Traffic Engineering Under Physical Layer Impairments	An integer linear programming and heuristic approach which consider aggregate effects of physical impairments and guarantee low bit error rate.
2011	Aparicio-Pardo et al.	Offline Impairment-Aware RWA and Regenerator Placement in Translucent Optical Networks	A novel Integer Linear Programming and heuristic approach which minimize lightpath interference and blocking.
2011	Katrnis et al.	On the Dimensioning of WDM Optical Networks With Impairment-Aware Regeneration	A novel integer linear programming and heuristic approach which helps in preventing trade-off between effectiveness of signal and cost of signal regeneration and which minimizes the total capital expenditure cost.
2012	Sengezer et al.	Multi-layer Virtual Topology Design in Optical Networks Under Physical Layer Impairments and Multi-hour Traffic Demand	An integer linear programming and heuristic approach to design a novel multilayer virtual topology.

2.2 Integer Linear Programming or Heuristic Based approaches

The three Research papers that are considered in this section use Integer Linear Programming (ILP) or Heuristic based approaches to solve the problem. All of this research adopts an ILP or a Heuristic approach to route lightpath requests under physical layer impairments. An initial approach was proposed by Christodoulopoulous et al. [2009] by extending the previous approach (RWA which do not consider impairments) and is followed by other approaches by various authors which are either new, extension or alteration to an existing technique and which focus on a small network and tries to provide a close to optimal solution to realistic problem.

2.2.1 *Integer Linear Programming approach.* Christodoulopoulos et al.[2009] state that certain physical effects which are sources of impairments are not taken into consideration during routing and wavelength assignment of lightpath to transfer data from source to destination. These impairments affects selection of lightpaths on itself as well as other lightpaths adjacent to it during routing and found that it was difficult for them to formulate in an offline algorithms. They state that there should be technique to incorporate such impairments an algorithm during routing and wavelength assignment so that experiment can be done which are exactly behaving as in real time scenario and come up with a solution which helps in minimizing the number of wavelengths used and also select lightpaths that have better quality of transmission.

The authors do not refer to any previous work. However, they identify drawback from the research previously done and state that physical layer impairments were not considered during routing of lightpaths.

The authors introduce the IA-RWA(Worst CaseIA-RWA) algorithm by extending the pure routing wavelength assignment algorithm taking into consideration the physical impairments which are generated by presence of other lightpaths or those that affect the same lightpath that generated them (assuming worst case scenario: where all lightpaths are active), using analytical model the effects of physical layer impairments for each candidate lightpath are calculated and only those which have acceptable quality of transmission are taken into consideration to transfer data and rest are ignored. The authors propose another algorithm which is a cross layer impairment aware routing wavelength assignment (sigma bound IA-RWA) the authors initially proceed by constraining the total number of adjacent, second adjacent channels and intra-XT interfering sources on a particular lightpath using mathematical methods which accounts for impairments that affect the same lightpath that generated them, the authors then consider noise variance which accounts the effects of the impairments caused by presence of other lightpaths. In sigma bound IA-RWA algorithm for a given lightpath after obtaining the number of adjacent channel and interfering sources for a particular lightpath it is multiplied with the noise variance and only those lightpaths that satisfy the corresponding noise variance constraints are the one which has acceptable quality of transmission and are used to transfer data.

The authors carried out different simulation experiments and implemented pure RWA and the proposed IA-RWA in Matlab and to evaluate the feasibility of lightpath Q-Tool developed with in the DICONET project was used. The topology used

was the Deutsche Telekom network with a capacity of each wavelength channel is 10 Gb/s.

The authors present the results obtained after conducting the experiments are presented in the form of histograms which graphs distribution of adjacent channels and number of intra XT interfering sources, and observed that there is a left shift in the probability distribution with sigma bound IA-RWA when compared with pure RWA which does not consider impairments. This indicates that the impairments generating sources are less and the quality of signal is more for a sigma bound IA-RWA compared to RWA. Moreover Sigma Bound-IA-RWA surpasses WC-IA-RWA by achieving zero blocking with few wavelengths and also with less number of rejected request calls for transmission of data.

The authors state that SB-IA-RWA gives better performance than the pure RWA algorithm which does not take into consideration the physical impairments or worst case IA-RWA which assumes that all lightpaths are active.

This paper is cited by Sengezer et al. [2010].

2.2.2 *Relaxed Integer Linear Programming approach.* Varvarigos et al. [2010] The authors state that signal quality degrades during transmission from source to destination due to physical layer impairments and also effects the routing choices made for a particular lightpath as well as other lightpaths which are transmitted along the same fiber. The authors state that there should be certain optimization techniques which help in providing connections by utilizing a minimum number of wavelengths but also helps in providing quality signal which is acceptable.

The authors do not to any previous work but identify shortcomings of previous approach by other authors working on the same problem. The authors state that decomposition techniques were followed in previous approaches which might not provide an optimal solution for the joint Routing and Wavelength Assignment problem, Apart from this, when taking into consideration interference, existing approaches do not consider the interference due to already established lightpaths on the candidate lightpath. Instead they assume a worst case scenario where all the lightpaths are active. The authors state that a new optimal technique should be formulated in order overcome existing problems and shortcoming of previous approaches.

The authors state that an initial approach was developed to solve the Routing and Wavelength Assignment problem without considering impairments based on Linear Programming relaxation formulation in order to generate integer solutions, then the algorithm is extended to two impairment aware routing, and a wavelength assignment algorithm was proposed that accounts for interference within lightpaths. The authors state that one approach takes physical impairments directly into account with the help of utilizing noise related parameters, whereas the other approach takes into effect the physical impairments indirectly and formulate a cross layer approach and helps in satisfying maximum number of requests (source to destination) with acceptable signal quality until it reaches the destination

The authors state that in order to test the proposed algorithms numerous simulation experiments were carried out in Matlab with random static instances. LINDO was used in order to solve the LP and ILP problems and the network topology used in their simulations was the generic deutsche Telekom network and the capacity

of the wavelength is considered to be 10 Gb/s. In order to evaluate the feasibility of the lightpaths a QoT tool was used with acceptable Q-factor equal to 15.5 dB. For evaluating the IA- RWA algorithm a link model with NRZ-OOK modulation format, 10-gb/s transmission rates and 50 GHz channel spacing with span length of 100km each having SSMF fibers with dispersion parameter of 17 ps/nm/km and attenuation of 25 db/km, was used.

The authors state that with traffic matrix load between 0.5 and 3 as input. The SB-IA-RWA scales well with the load. Considering realistic traffic matrix of DTnet in the simulation experiments the IA-RWA blocking ratio decreases significantly. The SB-IA-RWA can obtain a zero blocking solution, with running time about 15 min utilizing around 19700 variables and 22515 constraints for 35 wavelengths, about 3.2 percentage and running time around 3 hours utilizing 21338 variables and 61278 constraints for P-IA-RWA and 10 percentage with pure RWA and with running time around 30 seconds.

The authors claim that the approach of solving RWA problem based on LP-relaxation generates an optimal solution despite absence of integrality constraints for large instances. The authors further claim that the proposed two IA RWA algorithms which are P-IA-RWA and SB-IA-RWA show better performance than the pure RWA algorithm and moreover SB-IA-RWA shows better performance minimizing wavelength utilization providing zero-blocking solution with very less execution times.

2.2.3 *Heuristic, Meta-Heuristic or Combinatorial approach.* Sole et al. [2012] state that in a transparent network which transmits data in optical mode from end node to end node (thus reducing the expenses of converting the signal from optical to electrical and then to optical mode) there are chances of physical impairments accumulating on the signal during transmission which reduces the optical reach of the signal in the network and is also the source for other failures. The authors state that proper planning and operation phases should be taken care of in advance in order to avoid such problems, and there should also be certain techniques incorporated which take care of both physical and network layer interaction and which enable proper allocation of the resources and requirements so that optimal solution is obtained with maximum allocation of demands. In addition to this, the authors state that there should also be certain techniques which take into consideration integration of measurements of optical layer performance into algorithms which considers impairments on the lightpath signals during routing and wavelength assignment for optical networks to be capable of being automated and network configurable.

The authors refer to previous work by Aparicio-Pardo et.al [2011], and Varvarigos et.al [2009]

The authors state that change in currently used fiber capacity from several 10-gigs of data to several 100-gigs or 400-gigs of data poses technical problems and existing strategies does not apply to such wide capacity of fiber and these are yet to be investigated

The authors state that a cross layer strategy was developed which considers physical layer information, to overcome the problems under investigation.

The authors state that all the strategies developed were investigated with a 10gigs/sec system and infrastructure.

The authors state that there were no raw results obtained as no comparison of the different algorithm were carried out.

The authors claim that good Impairment Aware RWA algorithms were developed for protected and unprotected lightpaths with optimal monitor placement techniques.

2.2.4 *Summary.*

Year	Author	Title of Paper	Major Contribution
2009	Christodoulopoulous et al.	Considering physical layer impairments in offline RWA	Extended pure routing wavelength algorithm which considers impairments and provided a algorithm which is close to realistic scenario.
2010	Varvarigos et al.	Offline Routing and Wavelength Assignment in Transparent WDM Networks	An optimization technique which utilize minimum wavelengths and provide acceptable quality signal.
2012	Sole et al.	Cross-Layer Approaches for Planning and Operating Impairment-Aware Optical Networks	Technique which integrates optical layer performance which makes optical network automated and network configurable.

3. CITED BY

Author	Cited by
Christodoulopoulous et al. [2009]	Sengezer et al. [2010]
Manousakis et al. [2009]	Aparicio-Pardo et al. [2011] and Sole et al. [2012].
Pavon-Marino et. al [2009]	Aparicio-Pardo et al.[2011]
Sengezer et al. [2010]	Sengezer et al.[2012]
Aparicio-pardo et al. [2011]	Sole et al.[2012]

4. CONCLUDING COMMENTS

We note that Christodoulopoulos's group has conducted significant research in this area and is also referred by many other research groups, which shows the quality of their work.

Many of the approaches followed QoT threshold rather than taking distance i.e. optical reach where the signal tends to degrade its quality and errors in bits starts building up.

Many authors first explain the simple network where in most of the cases, the regular RWA involving Integer Linear Programming approach solves the problem and shows better performance, and then later on, extends to solve large or medium networks with the help of heuristic approach.

Most of the researchers used CPLEX in order to solve the integer linear programming and was given preference over other optimizers present.

All the researchers conducted experiments on standard real time networks present and did not vaguely or randomly formulate one.

The amount of data transferred per fiber ranges up to around 10 gigs per fiber and none of the researchers have considered a fiber carrying 100gigs/400 gigs or more. Imagine a collection of such fibers and each carrying 100gigs of data, few such fibers crossing a node leads to a real cost effective solution as with low cost large data can be transmitted. Taking into consideration the future scenario of increase in number of users this could help by carrying enormous amount of data through a fiber and make the communication quick and easy and have a low cost.

5. ACKNOWLEDGEMENT

I have the honour to acknowledge the knowledge, proficiency, expertise, judgment and guidance I received from Dr. Richard Frost throughout this survey. I convey my deep salutation to my supervisor Dr. Subir Bandyopadhyay for encouraging me, helping me throughly by providing me huge strength and support in completing this survey report and finally I would also like to thank Dr. Quazi Rahman, and Sajib Sinha for their time and continuous support through out my studies at University of Windsor.

6. ANNOTATIONS

6.1 Aparicio-Pardo et al. 2011

Citation:

Aparicio-Pardo, R., Klinkowski, M., Garcia-Manrubia, B. , Pavon-Marino, P., and Careglio, D. 2011. Offline Impairment-Aware RWA and Regenerator Placement in Translucent Optical Networks. *Journal of Lightwave Technology 29*,3, 26–277.

Problem: The authors state that physical layer impairments degrade the quality of optical signals during their transmission which cause the transmitted data not to be received correctly because of high bit error rate. There should be techniques which consider these physical impairments and avoid or minimize the lightpath blocking, interferences between lightpaths, and wavelength conversion and improving the quality of signal.

Previous Work: The authors refer to work done by K.Christodoulopoulos et al. [2009].

Shortcomings of Previous Work: The authors point out certain shortcomings from the paper referred and also from previous approaches on the same problem. The authors state that the existing approach which considers nonlinear variation of impairment (caused due to neighboring lightpaths in the networks) minimizing the bit error rate by placing regenerators and routing the signal according to the demand still has some demands blocked due to deteriorating quality of transmission and performance. In addition the authors do not consider the linear impairments caused due to the same lightpath. Therefore the authors state that the problem need to be solved by considering essential parameters which accounts for successful transmission of optical signal with maximum demands (requests) satisfying.

New Idea/Algorithm/Architecture: The authors propose an Integer Linear Programming model which considers physical layer linear impairments and which the authors claim to be a novel approach which was previously not done by any other researchers for a small or medium sized network. Apart from the ILP model the authors also propose a different heuristic approaches for a wide or large network which considers linear and non-linear physical impairments individually. The authors state that the technique or idea behind Integer Linear Programming was for each lightpath demand a set of valid semilightpaths which are optical signal traversing a sequence of fibers without undergoing any signal regeneration is calculated these semilightpaths forms a reachability graph which describes the ability of the semilightpaths to reach from one node to another, to improve the strength of the signal minimum number of regenerators planned are placed in order to improve and minimize the number of lightpaths which are blocked. This technique works for a small or medium size network and not for wide or large network, a new technique was proposed for such networks which is a heuristic approach and named it as Lightpath Segmentation, 3- Step Heuristic. The authors state that in Light path segmentation each candidate light path is divided or segmented into number of semilightpaths if the quality of signal measured by linear QoT estimator is less than the threshold, the degradation is caused by the physical layer linear impairments. The signals are made transparent by placing regenerators on the nodes which requires signal regenerations reducing the number of blocked light path requests, the algorithm minimizes such regenerator placement on nodes requiring signal regeneration and maximizes the number of lightpath requests from source to required destination. Here in order to make the formulation simple not all the valid semilightpaths are considered only few are considered and restriction is imposed. The authors state that a second heuristic approach called 3-step heuristic was also proposed which considers linear physical impairments in a large sized network. In this approach the authors initially allocate all the lightpaths without taking into consideration physical impairment, then check whether wavelength continuity is not satisfying and signal degradation is occurring if yes then place regenerators accordingly for wavelength conversion and improving the quality of the signal to avoid bit errors and also to minimize network blocking to allocates maximum number of lightpath requests. The authors propose another heuristic called Iterative Regenerator Placement (IRP) which considers nonlinear physical impairments and which uses nonlinear QoT estimator to evaluate the quality of lightpath or semilightpaths used. Initially all the lightpaths are routed and where the wavelength continuity is not satisfying wavelength converters are placed then an iterative regenerator placement is followed, through which semilightpaths approaching a particular nodes having worst Q factor has a regenerator placed on the node which has this as an outgoing semilightpath and along with it wavelength is also assigned this is an iterative process and continues until all the resulting semilightpaths have a valid Q factor along the signal.

Experiments Conducted: The authors take into consideration three reference network topologies in order to study the technique or approach proposed these reference topologies are INTERNET, NSFNET and NOBEL-EU, for a medium size network which is INTERNET, NSFNET 8, 16 wavelengths were tested per fiber

and 80 wavelengths were tested in case of NOBEL-EU. The authors utilize Q-Personick factor in order to represent linear and non-linear QoT estimation, which considers 17 dB as maximum threshold of the acceptable Q-factor, which is also used as reference to validate the quality of a semilightpath which has a maximum link length as 2688 Km. In order to test authors consider a network topology, three traffic loads matrix which are low, medium, high which has traffic load factor as 0.4, 0.7, 1, with certain wavelengths per fiber the maximum number of lightpath demands are calculated and later the effects of network link lengths on the regenerator equipment cost planned are tested.

Results: The authors state that the heuristics LS and Three-Step algorithms provide similar optimal solution and in specific LS algorithm provided better solution compared to rest algorithms as it requires less number of regenerators to be placed along with also having minimum lightpath blocking capability when considering linear impairments. By observing the results of the three different algorithms which consider linear impairments only it can be said that small sized networks do not require regeneration equipment at all and it is topological dependent. Drawing attention towards the execution time for the proposed algorithms which takes into consideration linear impairments and comparing among it the authors state that it can be observed that three-step algorithm has execution time below 1 second and highest execution time was observed in the ILP formulation method but LS showed variation in the execution time, it was less than one second in Internet and NSFNET network topologies most of the cases of inputs provided and it increased with increase in network size. The authors also conducted what they claim to be exhaustive testing taking into consideration non-linear impairments using iterative routing placement algorithm and observed that it outperforms ILP which considers physical hops (PH-ILP) and also has a better execution time.

Claims: The authors state that the non-linear IA-RWA-RP algorithm is best, in both lightpath blocking and regenerator cost, compared to PH-ILP and whereas in linear IA-RWA-RP the LS and three-step heuristics provide optimal or close to optimal solutions in all tests conducted. In addition, the three-step algorithm guarantee that no signal regeneration blocking is produced

Citations by Others: Sole et al.[2012]..

6.2 Christodoulopoulos et al. 2009

Citation:

Christodoulopoulos, K., Manousakis, K., and Varvarigos, E., 2009. Considering Physical Layer Impairments in Offline RWA. *Network, IEEE 23,* June, 26–33.

Problem: The authors state that certain physical effects which are sources of impairments are not taken into consideration during routing and wavelength assignment of lightpath to transfer data from source to destination. These impairments effects selection of lightpaths on itself as well as other lightpaths adjacent to it during routing and found that it was difficult for them to formulate in an offline algorithms. They state that there should be technique to incorporate such impairments in an algorithm during routing and wavelength assignment so that experiment can be done which are exactly behaving as in real time scenario and

come up with a solution which helps in minimizing the number of wavelengths used and also select lightpaths that have better quality of transmission.

Previous Work: There was no previous work referred by authors but in general state certain drawback from the research previously done in the same field.

Shortcomings of Previous Work: The authors state that physical layer impairments were not considered during routing of lightpaths.

New Idea/Algorithm/Architecture: The authors introduce the IA-RWA(Worst CaseIA-RWA) algorithm by extending the pure routing wavelength assignment algorithm taking into consideration the physical impairments which are generated by presence of other lightpaths or those that affect the same lightpath that generated them (assuming worst case scenario: where all lightpaths are active), using analytical model the effects of physical layer impairments for each candidate lightpath are calculated and only those which have acceptable quality of transmission are taken into consideration to transfer data and rest are ignored. The authors propose another algorithm which is a cross layer impairment aware routing wavelength assignment (sigma bound IA-RWA) the authors initially proceed by constraining the total number of adjacent, second adjacent channels and intra-XT interfering sources on a particular lightpath using mathematical methods which accounts for impairments that affect the same lightpath that generated them, the authors then consider noise variance which accounts the effects of the impairments caused by presence of other lightpaths. In sigma bound IA-RWA algorithm for a given lightpath after obtaining the number of adjacent channel and interfering sources for a particular lightpath it is multiplied with the noise variance and only those lightpaths that satisfy the corresponding noise variance constraints are the one which has acceptable quality of transmission and are used to transfer data.

Experiments Conducted: The authors carried out different simulation experiments and implemented pure RWA and the proposed IA-RWA in Matlab and to evaluate the feasibility of lightpath Q-Tool developed with in the DICONET project was used. The topology used was the Deutsche Telekom network with a capacity of each wavelength channel is 10 Gb/s.

*Results:*The authors present the results obtained after conducting the experiments are presented in the form of histograms which graphs distribution of adjacent channels and number of intra XT interfering sources, and observed that there is a left shift in the probability distribution with sigma bound IA-RWA when compared with pure RWA which does not consider impairments. This indicates that the impairments generating sources are less and the quality of signal is more for a sigma bound IA-RWA compared to RWA. Moreover Sigma Bound-IA-RWA surpasses WC-IA-RWA by achieving zero blocking with few wavelengths and also with less number of rejected request calls for transmission of data.

Claims: The authors state that SB-IA-RWA gives better performance than the pure RWA algorithm which does not take into consideration the physical impairments or worst case IA-RWA which assumes that all lightpaths are active.

Citations by Others: This paper is cited by Sengezer et al. [2010].

6.3 Katrinis et al. 2011

Citation:

Katrinis, M. and Tzanakaki, A. 2011. On the Dimensioning of WDM Optical Networks with Impairment-Aware Regeneration *IEEE/ACM Transactions 19,* 3, 735–746.

Problem: The authors state that the quality of a signal degrades as it propagates through the optical medium and there should be techniques which take into account impairments caused due to physical layer during transmission, ways to strengthen the signal quality, and methods to determine how many signals should be deployed in a network in order to avoid signal degradation. The authors also state that techniques developed should be of low cost with an ability of signals to reach long distances without compromising signal quality and avoid any tradeoff between effectiveness of signal and cost of signal regeneration.

Previous Work: The authors do not refer to any paper which is present in list of papers selected which are exactly on topic.

Shortcomings of Previous Work: The authors state certain drawback from the previous approaches proposed in the same area of problem and state that with the existing techniques there was clear tradeoff between the number of regenerators to be placed and the capacity of the WDM network. There was more concentration on routing aspects rather than design of the network which is the most important before routing any light path demand. The authors also state that the existing methods assumed that the distance covered by lightpath is a good approximation of signal quality degradation which is not necessarily true and further it holds good only for cases where there are limited number of hops and for networks exhibiting high homogeneity of optical equipment.

*New Idea/Algorithm/Architecture:*The authors state that a new Integer Linear Programme was formulated, which according to authors was not previously stated by others in the literature and they consider it to be a novel approach. The authors state that the main aim of their ILP formulation is to specify the capacity (which is the number of fibers), number of links (Edges) through which a candidate path travels, number of wavelength per fiber it supports and minimize the total cost occurring of the dimensioned (the optimization of the capacity put on deployed network) network.

*Experiments Conducted:*The authors state that inorder to test the ILP formulation proposed, the ILOG CPLEX v.11.1.1 mathematical programming engine was used for solving the Integer Linear Program instances. Impairment models were used to evaluate the Bit Error Rate throughout the experiment. The hardware utilized during the experiment was Intel Xenon CPU 2.80 GHz Linux workstation, equipped with 2GB RAM. The network topology utilized was NSFNET comprising of 16 nodes and 48 physical links, in regards to input traffic requests a randomly generated traffic matrix with 70 nonzero source/destination pairs, with 344 wavelengths was used, apart from it noise figures of amplifiers which are modeled using a normal distributed random variable with certain standard deviation and step level was used for the purpose of evaluation of optical equipment configuration.

Results: The authors state that for optical reach values from 500 to 1250km and low heterogeneity (variation in optical equipment) percentage of impaired lightpaths was from 0 to 2.5 percentage for network dimensioning in combination with length-based regeneration. As the degree of heterogeneity increased the percent-

age of impaired lightpaths increased from 2.5 percentage to 14.6 percentage. For optical reach 1500 km and 1750 km the percentage of impaired paths went upto 21 percentage. The authors also state that 90 percentage of saving in regenerators with IA Regenerator placement approach was seen for optical reach which is 500 and for various heterogeneity levels and then for optical reach 1750 the impairment aware regenerator placement has 60 percentage saving in regenerators used. When considering the case of uncertainty of heterogeneous levels impairment aware regenerator placement has on average of 138-209 regenerators used on average, specific to heterogeneity level 5 the saving was 35 percentage on average and yielding 10 percentage impaired paths on average.

Claims: The authors claim that the results obtained from the experiments show their approach has better results than the previous approach which considers placing regenerators based on the length rather than based on the quality of signal and achieved less regeneration cost along with providing good signal quality.

Citations by Others: There was no citation done by the authors from the list of most important papers referred on topic.

6.4 Manousakis et al. 2009

Citation:

Manousakis, K., Christodoulopoulos, K., Kamitsas, E., Tomkos, I., and Varvarigos, E. 2009. Offline Impairment-Aware Routing and Wavelength Assignment Algorithms in Translucent WDM Optical Networks. *Journal of Lightwave Technology 27,* 12, 1866–1877.

Problem: The authors state that during transmission of an optical signal the existence of physical impairments in optical fibers block the connection requests from reaching the destination. There should be efficient algorithms to re-route blocked connections by selective placement as well as selective use of minimum number of regenerators which re-shapes, re-amplify and re-time the signal.

Previous Work: The authors refer to work of Manousakis et.al [2009].

Shortcomings of Previous Work: The authors state no exact short comings in the approach referred but points out the shortcomings in general taking the over all scenario and state that in the previous approaches proposed used regenerators at every node which do not provide a cost effective solution and is a huge drawback and few other approaches do not consider the impairment effect at all.

*New Idea/Algorithm/Architecture:*The authors state that a new impairment aware algorithm was designed and implemented for routing and wavelength assignment along with solving regenerator placement and assignment problem in translucent networks which places regenerators at selective sites along with the number of regenerators to be placed. The authors state that the placement and assigning of regenerators is considered as a virtual topology design problem which utilize various ILP and greedy heuristic algorithms to solve it and apart from that the approach also determines sequence of regenerators to be utilized by the connections having impairments and transform the non-transparent connection to transparent signal by terminating and regenerating the signal at the specified intermediate node and minimize the number of blocked connections.

Experiments Conducted: The authors state that in order to evaluate the per-

formance of the proposed impairment aware RWA algorithm numerous simulation experiments were performed with the IA-RWA algorithm. Virtual topology algorithms were implemented in Matlab and LINDO API was used to solve ILP related problems in order to evaluate the feasibility of lightpath. The Q-factor estimator was used in the experiment. The link model has a NRZ-OOK modulation format, 10 Gbps transmission rates, 50 GHz channel spacing with span length equals to 80km with Geant-2 network topology with 34 nodes and 54 bidirectional links.

*Results:*The authors state that when the blocking ratio is graphed against the number of available wavelengths and demands the PH-based algorithms shows a blocking probability ranging from 0.05 to 0.00 and required wavelengths ranging from 90 to 110 to reach zero blocking with the number of demands varying from 700 to 400. Moreover the PH-ILP sum of regenerator algorithm required 115wavelengths and 461 regenerators while the VP-ILP sum of regenerator required 135 and 430 regenerators to reach zero blocking. In addition, the execution time of the IA-RWA algorithm for translucent network requires about 3 hours in which application of IA-RWA algorithm used by transparent network in translucent network consumes most of the time and the remaining phases requires only few 10s of seconds.

Claims: The authors state that with the use of the Q factor, low complexity of the virtual topology design problem make the approach efficient for small and large scale heterogeneous mesh networks. Among various algorithms proposed for the virtual topology design problem the ILP formulation helps in reducing the maximum number of regenerators to be placed and among the heuristics proposed the physical Hop heuristic exhibit better performance and stable function in all cases.

Citations by Others: This paper is cited by Aparicio-Pardo e al. [2011] and sole et al. [2012].

6.5 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.

Problem: The authors state that the quality of signal degrades due to physical layer impairment and if there are no regenerators there are chances of bit errors to be more which in turn weakens the signal strength. The authors state that there should be appropriate techniques which consider impairments during signal transmission and help in serving maximum number of connections

Previous Work: The authors state that there is no paper referred by the authors.

Shortcomings of Previous Work: No shortcomings are mentioned by the authors.

New Idea/Algorithm/Architecture: The authors state that an IA-RWA offline algorithmic approach is followed which performs a cross layer optimization between the physical and network layers present and take into account the directly the dominant impairment effect and upper bound on the interference noise variance it can tolerate is calculated and it is used as constraint the interfering noise caused

by other lightpaths and avoid heavy ILP formulations.

Experiments Conducted: The authors state that the performance of the proposed crosses layer optimization is evaluated through simulations, MATLAB, LINDO API to solve related LP problems, generic DTnet topology. The capacity of a wavelength assumed equals to 10Gbps and finally to evaluate the feasibility of lightpath physical layer evaluation module was developed.

*Results:*The authors state that assuming 16 wavelengths and random 100 traffic matrix the proposed IA-RWA algorithm manages to serve all the traffic matric upto load equals 0.8 with zero physical and networking blocking. For load equals 2.05 and for wavelengths=35 the pure RWA algorithm has blocking equal to 10 percentage while the IA-RWA has blocking equal to 0 percentage and running time was about 20min.

*Claims:*The authors claim that the cross layer optimization minimizes the number of wavelength used in the network and also select lightpaths with acceptable quality of transmission. The proposed algorithm has better performance improvement when compared to typical RWA algorithm.

Citations by Others: This paper is cited by Aparicio-Pardo et al. [2011].

6.6 Sengezer et al. 2010

Citation:

Sengezer, N. and Karasan, E. 2010. Static Lightpath Establishment in Multilayer Traffic Engineering Under Physical Layer Impairments. *IEEE/OSA Journal of Optical Communications and Networking 2,* 9, 662–677.

Problem: The authors state that there is problem in establishing static versions of lightpath requests which consider physical impairments in the optical layer which is the backbone of the lower layer in the multilayer architecture which consists of a Service layer, Electrical layer and Optical layer. The authors state that there is a need to formulate efficient algorithms in order to satisfy maximum lightpaths (requests) with minimum blocking and bit error rates of the established lightpaths and make efficient use of the bandwidth allocated for transmission of data.

Previous Work: The authors refer to previous work by Christodoulopoulos et al. [2009].

Shortcomings of Previous Work: The authors state that the existing method was not investigated in detail and there was only a basic comparison with other methods which do not consider impairments and no further study was done. The authors state that there are many other factors which influence a lightpath to satisfy a demand and must be taken into consideration and investigated further.

*New Idea/Algorithm/Architecture:*The authors propose an Integer Linear Programming (ILP) formulation for static lightpath establishment which considers physical layer impairments. The idea behind the ILP formulation is to route as many lightpath demands by making use of the resources provided. In formulating the ILP the authors considered the aggregate effect of the physical impairments through which low Bit Error Rate is guaranteed which is below the acceptable threshold. A set of paths for each source-destination are generated and each request is routed through paths chosen and at every level a link capacity constraint is imposed. A physical impairment model is used to provide with upper limit of

impairments a lightpath can handle when it is routed from the source, and the level at the receiver is monitored using a linear expression which represent the noise level due to ASE, Cross-talk and by the signal itself. The authors state that there is a drawback in the ILP formulation as the size of the network increases the solution time also increases exponentially, which makes it infeasible for a large size network. To overcome this drawback a polynomial time heuristic approach called ROLE (ReOrdered Lightpath Establishment Algorithm) was formulated taking into consideration large size networks the objective of the heuristic is to route as many requests as possible taking consideration of the Bit Error Rate constraint and not violating it. The authors formulated the ROLE heuristic in three phases first is Routing and Wavelength Assignment, rerouting and reordering. In Routing and Wavelength Assignment shortest path is selected along with an available wavelength and best combination is looked for a particular lightpath demand. After RWA rerouting is performed in order to improve the results of the RWA phase, which has a few lightpaths blocked due to no available wavelength or due to BER threshold. The algorithm first tries to route the BER blocked demands and then wavelength blocked demands so that minimum node cross talk is achieved. In case of reordering the authors state that all the unsatisfied lightpath requests are made to undergo RWA and rerouting until there are no unsatisfied lightpath demands.

Experiments Conducted: The authors state that in order to evaluate the performance of the ROLE algorithm proposed, and to make comparison with other approaches as well as to compare with itself based on sorting techniques, a randomly generated physical topology each with 20 nodes having 25-40 bidirectional links (topology1, topology2, topology3, topology4) using three different wavelengths 4,8,16 and which has the required lightpath demands generated randomly sorted in either shortest lightpath demand, longest lightpath demand was utilized. Experiments were also carried out on realistic Deutsche Telekom network topology in order to make a valid comparison with other proposed procedures. The ILP algorithm proposed by the author was solved using ILOG CPLEX optimizer which uses branch and cut method was compared with ROLE for a very small network and performance was evaluated.

Results: According to the authors experiments on ROLE algorithm with taking into consideration both shortest demand first and longer demand first on various topologies shows percentage of routed lightpaths is from 65 for topology1 to 87 for topology4.

Claims: The authors claims that the proposed ROLE algorithm performed 14 percentage better than the best heuristic algorithm present so far (POLIO-RWA) for the same problem, and is also guaranteed to provide optimum solutions for different sets of demands for different network sizes.

Citations by Others: This paper is cited by Sengezer et al.[2012].

6.7 Sengezer 2012

Citation:

Sengezer, N. and Karasan, E. 2012. Multi-layer Virtual Topology Design in Optical Networks Under Physical Layer Impairments and Multi-hour Traffic Demand *EEE/OSA Journal Journal of Optical Communications and Networking 4* , 2, 78.

*Problem:*The authors state that there is a need for proper topology design through which we can obtain less or no wavelength conversion at all during transmission of an optical signal considering physical impairments along its path. There is a need for design or a approach in which sharing of information between various layers in the wavelength division multiplexing network is taken care of in order to attain blocking-free performance and best utilization of resources available.

Previous Work: The authors refer to work done by Varvarigos et.al [2009], Sengezer et.al [2010]

Shortcomings of Previous Work: The authors point out certain shortcomings from the previous approaches referred as well as other techniques which are used to solve the problem and state that in the previous approaches the solutions obtained was not traceable for moderate or large size networks as the whole problem was divided into sub problems and there should also be care taken during integration of solutions obtained at every phase and if there is a mistake then we would not obtain optimal solution at all. The authors also state that all the subproblems consider only one layer and omit other layers present and ignore sharing of information also during its transmission in an optical network and physical layer impairments are also ignored. A heuristic approach formulated provided solution but it was observed that excess utilization of wavelengths than used was possible and further does not provide optimal solution.

New Idea/Algorithm/Architecture: The authors state that their approach is first of its kind in the area to solve the problem. They introduce, what they claim to be, a novel multilayer virtual topology design approach in which both wavelength assignment and physical layer impairments are considered, and which involves interaction of control planes of multi-protocol label switching and wavelength division multiplexing layers during topology design and share information using topology information sharing strategy in which a wavelength routing node architecture was followed in physical layer model. The authors also propose two topology designs: a) Tabu search virtual topology design b) Greedy search virtual topology design in order to solve multilayer virtual topology design. Apart from this a mixed integer linear programming approach was made to provide a bench mark to evaluate the performance of other approaches to the multi-layer VTD problem.

Experiments Conducted: The authors state that in order to evaluate the performance of the VTD algorithms and information strategies with different traffic rates and patterns changing with time. A wide area network is utilized with NSFNET topology with 21 links and 14 nodes spread over four different time zones. Apart from this inorder to evaluate the topology design algorithms CPLEX 12.1 optimization problem solver was used.

Results: The authors state that on conducting experiment with 15 percentage traffic magnitude with 21 links and 14 nodes MILP shows 31.9, GS-VTD shows 27.82, TS-VTD with out layer interaction shows 36.7 and TS-VTD with layer interaction shows 0.03 percentages of bandwidth blocking and for a whole day time period blocking ratio for a single-hour traffic demand was 3.19 percentage and for multi-hour traffic demand it was 2.40 percentage both having 100 percentage traffic intensity.

Claims: The authors claim that the proposed method solves the multi-layer

logical topology design and LSP routing problems arising in MPLS layers, and routing and wavelength assignment problems in the wdm layers in an integrated approach that does not necessitate a single common control plane for both layers. The authors also state that MILP formulation approach does not generate good solutions and when taking into consideration heuristic approach Tabu search based algorithm can reduce the blocking ratio of the GS-VTD algorithm by 35 to 100 percentage.

6.8 Sole et al. 2012

Citation:

Sole, J., Subramaniam, S., Careglio, D. and Spadaro, S. 2007. Cross-Layer Approaches for Planning and Operating Impairment-Aware Optical Networks. In *Proceedings of the IEEE 100,* 5, 1118—1129.

Problem: The authors state that in a transparent network which transmits the data in optical mode from end node to end node (thus reducing the expenses of converting the signal from optical to electrical and then to optical mode) there are chances of physical impairments accumulating on the signal during transmission which reduces the optical reach of the signal in the network and is also the source for other failures. The authors state that proper planning and operation phases should be taken care of in advance in order to avoid such problems, and there should also be certain techniques incorporated which take care of both physical and network layer interaction and which enable proper allocation of the resources and requirements so that optimal solution is obtained with maximum allocation of demands. In addition to this, the authors state that there should also be certain techniques which take into consideration integration of measurements of optical layer performance into algorithms which considers impairments on the lightpath signals during routing and wavelength assignment for optical networks to be capable of being automated and network configurable.

Previous Work: The authors refer to previous work by Aparicio-Pardo et.al [2011], Varvarigos et.al [2009].

*Shortcomings of Previous Work:*The authors state that change in currently used fiber capacity from several 10-gigs of data to several 100-gigs or 400-gigs of data poses technical problems and existing strategies does not apply to such wide capacity of fiber and these are yet to be investigated

New Idea/Algorithm/Architecture: The authors state that a cross layer strategy was developed which considers physical layer information, to overcome the problems under investigation.

Experiments Conducted: The authors state that all the strategies developed were experimented with a 10gigs/sec system and infrastructure.

Results: The authors state that there were no raw results obtained as no comparison of the different algorithm results were made.

Claims: The authors claim that good Impairment Aware RWA algorithms were developed for protected and unprotected lightpaths with optimal monitor placement techniques.

Citations by Others: There are no explicit implication to this paper by other researchers in this survey.

6.9 Varvarigos et al 2010

Citation:

Varvarigos, E., Manousakis, K. and Christodoulopoulos, K. 2010. Offline Routing and Wavelength Assignment in Transparent WDM Networks *IEEE/ACM Trans. on Networks 18*, 5, 1557—1570.

Problem: The authors state that signal quality degrades during transmission from source to destination due to physical layer impairments and also effects the routing choices made for a particular lightpath as well as other lightpaths which are transmitted along the same fiber. The authors state that there should be certain optimization techniques which help in providing connections by utilizing a minimum number of wavelengths but also helps in providing quality signal which is acceptable.

*Previous Work:*The authors do not to any previous work from the list of papers present which are exactly on topic.

Shortcomings of Previous Work: The author states certain short coming in the previous approach by other authors working on the same problem. The authors state that decomposition techniques were followed in previous approaches which might not provide an optimal solution for the joint Routing and Wavelength Assignment problem, Apart from this, when taking into consideration interference, existing approaches do not consider the interference due to already established lightpaths on the candidate lightpath. Instead they assume a worst case scenario where all the lightpaths are active. The authors state that a new optimal technique should be formulated in order overcome existing problems and shortcoming of previous approaches.

*New Idea/Algorithm/Architecture:*The authors state that an initial approach was developed to solve the Routing and Wavelength Assignment problem without considering impairments based on Linear Programming relaxation formulation in order to generate integer solutions, then the algorithm is extended to two impairment aware routing, and a wavelength assignment algorithm was proposed that accounts for interference within lightpaths. The authors state that one approach takes physical impairments directly into account with the help of utilizing noise related parameters, whereas the other approach takes into effect the physical impairments indirectly and formulate a cross layer approach and helps in satisfying maximum number of requests (source to destination) with acceptable signal quality until it reaches the destination

*Experiments Conducted:*The authors state that in order to test the proposed algorithms numerous simulation experiments were carried out in Matlab with random static instances. LINDO was used in order to solve the LP and ILP problems and the network topology used in their simulations was the generic deutsche Telekom network and the capacity of the wavelength is considered to be 10 Gb/s. In order to evaluate the feasibility of the lightpaths a QoT tool was used with acceptable Q-factor equal to 15.5 dB. For evaluating the IA- RWA algorithm a link model with NRZ-OOK modulation format, 10-gb/s transmission rates and 50 GHz channel spacing with span length of 100km each having SSMF fibers with dispersion parameter of 17 ps/nm/km and attenuation of 25 db/km, was used.

Results: The authors state that with traffic matrix load between 0.5 and 3 as

input. The SB-IA-RWA scales well with the load. Considering realistic traffic matrix of DTnet in the simulation experiments the IA-RWA blocking ratio decreases significantly. The SB-IA-RWA can obtain a zero blocking solution, with running time about 15 min utilizing around 19700 variables and 22515 constraints for 35 wavelengths, about 3.2 percentage and running time around 3 hours utilizing 21338 variables and 61278 constraints for P-IA-RWA and 10 percentage with pure RWA and with running time around 30 seconds.

Claims: The authors claim that the approach of solving RWA problem based on LP-relaxation generates an optimal solution despite absence of integrality constraints for large instances. The authors further claim that the proposed two IA RWA algorithms which are P-IA-RWA and SB-IA-RWA show better performance than the pure RWA algorithm and moreover SB-IA-RWA shows better performance minimizing wavelength utilization providing zero-blocking solution with very less execution times.

Citations by Others: There are no explicit implication to this paper by other researchers in this survey.

6.10 Zhang et al. 2009

Citation:

Zhang, W., Tang, J., Nygard, K., and Wang, C. 2009. REPARE: Regenerator Placement and Routing Establishment in Translucent Networks. *GLOBECOM 2009 - 2009 IEEE Global Telecommunications Conference,* 1—7.

Problem: The authors state that most of research done in designing and routing optical signals assumes that the medium in which the data is transferred passes without any error in bits. But in fact the situation of non-erroneous transfer of data may not really occur since there are chances that some physical impairment may be introduced by the optical fibers or other components utilized to route optical signals. The authors state that such impairments should be taken into consideration while designing and routing optical signal and there should be appropriate techniques to transfer data with the help of optical signals without any bit errors during transmission and look into providing an efficient and effective routing of optical signal.

Previous Work: The authors state that there is no previous work referred by the authors.

*Shortcomings of Previous Work:*The authors state certain shortcomings in general taking the over all scenario. The authors state that even though physical impairments are considered during transmission of optical signals, there is no assurance of a particular request being accepted in order to transmit data because the signal could possibly generate high bit error rate and requests could be rejected. Hence many optical signal requests can not be accepted because of chances that it could not keep up the quality of the signal due to impairments, which makes the whole network inefficient to accept many source and destination requests. Therefore there should be techniques to convert the inefficient signal to efficient signal even though some cost is involved so that we can increase the overall network utilization up to its maximum capability.

New Idea/Algorithm/Architecture: The authors state that during transmission of

an optical signal, impairments are caused by the optical fibers or components used in the optical network which in turn is responsible for bit errors. To overcome the problem of bit errors during transmission of optical signals the authors introduce a novel Integer Linear Programming (ILP) formulation for small networks and a heuristic approach for a large network which places minimum number of 3R regenerators (where each R= reshaping, R= retiming, R= reamplification) in an efficient and effective way with optical electrical optical conversion capability to accommodate all requests.

Experiments Conducted: The authors state that in order to compare and evaluate the performance of the proposed methods the pacific bell network topology was used to test the network which has 15 nodes and 21 links with 32 wavelengths per fiber capability apart from that CPLEX was also used to solve the ILP formulation to generate an optimal solution. The simulation was performed on a machine with a Intel Pentium 1.70GHz CPU and 512 MB memory.

*Results:*The authors state that for traffic matrix size upto 70 starting from 50 size, nearly 4 regeneration nodes were required for ILP formulation method and for heuristic method it was varying from five to seven and beyond 70 traffic matrix size, ILP could not generate solution. In case of the heuristic approach it generated a feasible solution as the traffic matrix size increases. The running time performance for ILP to generate solution was 1000 millisecond whereas for a heuristic to generate a solution it was taking a few milliseconds.

Claims: The authors claim that the results obtained from the experiments show that their heuristic algorithm outperforms the ILP optimal solution for various traffic matrices and showed better result and performance than the ILP optimal solution.

Citations by Others: There are no explicit implication to this paper by other researchers in this survey.

7. REFERENCES

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