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Impairment and Regenerator Aware Lightpath Setup Using Distributed Reachability Graphs

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***Abstract*— GMPLS-based transparent optical networks suffer from accumulation of physical layer impairments (PLIs) along the optical path and inefficient wavelength utilization due to wavelength continuity constraint. To increase the optical reach, resource utilization, and average call acceptance ratio, network operators resort to translucent optical networks in which a limited number of regenerators are placed at a selected set of nodes. In this scenario development of an optical control plane which is aware of PLIs, location and number of regenerators, is of paramount importance for on-demand lightpath provisioning. In this paper, we propose a novel three phase approach—reachability graph construction, route computation on reachability graph, and signaling—impairment and regenerator aware routing and wavelength assignment (IRA-RWA). We also propose corresponding GMPLS protocol extensions. The simulation results suggest that our proposed approach together with LSP stitching signaling mechanism can be deployed in real-world translucent optical networks.**

***Keywords-** GMPLS-based translucent optical networks, physical layer impairments, reachability graph, LSP stitching*

I. INTRODUCTION

In transparent optical networks, impairments incurred by non-ideal optical transmission media accumulate along an optical transmission path, and determine the quality of transmission (QoT) of the lightpath [1-3]. If the received optical signal quality is not within the receiver sensitivity threshold, the receiver may not be able to correctly detect the optical signal, causing the lightpath and corresponding resources to be useless. In addition, transparent optical networks also suffer from inefficient wavelength utilization due to inherent wavelength continuity constraint of transparent WDM optical networks. To increase the optical reach, resource utilization, and acceptance rate, network operators resort to optical-electrical-optical (OEO) regenerators. However, as OEO regenerators are expensive, operators are forced to reduce the total number of regenerators in the network, and hence CAPEX, without compromising the network performance.

Translucent optical networks can be viewed as an intermediate step in moving from opaque networks towards transparent networks. In these networks, the signal will be regenerated only when its QoT falls below a threshold or a wavelength contention has to be resolved along the optical path. Hence, translucent networks need less number of regenerators compared to opaque networks which translates into enormous cost reduction [4]. In this paper, we consider translucent optical networks in which a limited number of regenerators are placed at a selected set of network nodes.

In this scenario, development of an optical control plane (OCP) which is aware of impairments and location and number of available regenerators is of paramount importance for on-demand lightpath provisioning in generalized multiprotocol label switching (GMPLS)-based translucent optical networks. The presence of regenerators requires several algorithms to decide which regenerators should be used while setting up *a translucent lightpath—an end-to-end lightpath composed of multiple transparent segments*. We propose a novel method to construct a reachability graph (RG) of a given network on which the lightpath requests are routed if there is no transparent path. *The reachability graph contains all the network nodes and a new set of links that represent which nodes can reach the regenerator nodes transparently.* The shortest path computed on the RG is a translucent lightpath identifying the selected regeneration sites as fixed nodes along the route. To implement the proposed OCP, several extensions are proposed to: open shortest path first with traffic engineering (OSPF-TE) to disseminate the required information for RG construction and resource reservation protocol with traffic engineering (RSVP-TE) to validate the optical feasibility of transparent or translucent lightpaths using the label switched path (LSP) stitching mechanism [5]. It also evaluates the effect of new LSP on the active LSPs and avoids active LSP disruption.

II. RELATED WORK

Several methods for lightpath establishment in translucent networks have been proposed in the literature. In [6-9] heuristics algorithms are developed considering only linear impairments (LIs) and assuming bit error-rate (BER) as feasibility constraint. These heuristics work well in centralized environment, but difficult to implement them in distributed OCP. These heuristics could be implemented in real-world networks using path computation element (PCE) approach. However, centralized PCE approach has several disadvantages due to single point failure, etc., [1]. In [10] a distributed algorithm is developed based on the construction of auxiliary graph taking into account of PLIs and wavelength availability. However, it assumes the translucent networks with selected nodes as opaque nodes. The work in [11] is similar to [10] however; it did not consider wavelength availability information in the routing phase. In [12] two algorithms are developed considering worst case penalties for LIs, cross-phase modulation (XPM), and four wave mixing (FWM) and feasibility constraint as Q-factor. A signaling-based mechanism is developed in [13, 14] to consider LIs and self-phase modulation (SPM). Hybrid OCP architecture is developed in [15] based on [13, 14]. In hybrid OCP, the regenerator availability information is disseminated in the network using extended OSPF-TE. In [12-16] the feasibility constraint used is BER and Q-factor with a relation to optical signal to noise ratio (OSNR). In [12-16] either the source or intermediate nodes designates the required regenerator nodes on the shortest path depending on if the regenerator availability information at the source node or signal quality at the intermediate node is in the critical range, respectively. However, these methods do not consider the impact of new LSP on active LSPs.

In general, most of the literature uses approximate estimation of PLIs considering only LIs or approximate models or worst-case penalties and propose routing mechanisms that minimize the regenerator usage, while giving preference to the links with more available regenerators or wavelengths. The main limitation of these approaches is the limited accuracy of optical feasibility evaluation resulting in establishment of optically unfeasible paths. Few studies [12-16] rely on signaling to perform regenerator selection on the shortest path and optical feasibility check. As noticed in [12], the regenerator selection during signaling phase results in several setup attempts due to crank-back. A common limitation of the existing approaches [5-12] is inaccurate modeling of multi-channel effects, e.g. FWM or XPM, which could potentially lead to disruption of active LSPs due to excessive crosstalk introduced by new LSP. In [13-16] no mechanism is proposed to deal with potential active LSP disruption. Recently, we proposed an innovative mechanism to detect and avoid potential active LSP disruption in transparent networks [3], which is extended here to translucent networks. We note that following steps can increase the overall network performance: 1) *dissemination* of static PLIs, regenerator, and wavelength availability information using OSPF-TE; 2) enhanced *route computation* using this information and approximate PLIs models; and 3) *accurate feasibility check* with detection and avoidance of potential active LSP disruption in the signaling phase. Accordingly, we propose a three phase distributed hybrid OCP in the next section.

III. Proposed Hybrid OCP Approach

In this section we propose a novel three phase hybrid OCP approach based on extensions to OSPF-TE and RSVP-TE.

A. *Problem Definition and Assumptions*

In our work, we assume that all regenerators are *colorless* and *directionless;* however, the framework can be easily extended to other architectures. The regenerator sites are selected using the algorithm in [17]. All the LSP requests are bidirectional. The objective is to find either a feasible transparent path (if it exists) or a translucent path—multiple transparent segments with minimum number of regenerators—in minimum number of setup attempts, while making sure that the setup of new LSP does not disrupt any active LSPs.

In current literature on GMPLS-based optical networks, the establishment of the LSP is carried out in two main phases: *route computation phase* (RCP) and *signaling phase (SP)*. The RCP provides a set of most likely feasible transparent or translucent paths ordered with respect to minimum resources required (e.g. regenerators). This is because the source node has only partial or no knowledge of PLIs and hence RCP can not guarantee the optical feasibility of the paths. The SP which carries all required PLIs information validates the LSP optical feasibility. If the path given by the RCP is optically feasible then the resources required for the new LSP are reserved. Validating the optical feasibility in the SP may increase the number of setup attempts. Hence, it is important for the RCP to minimize the likelihood of performing several attempts by using PLIs and regenerator availability information; particularly in large networks where several feasible paths are available; which motivates us to introduce *reachability map computation phase* discussed in this section. Note that there is no mechanism to check if the setup of new LSP disrupts any active LSPs in the network by introducing excessive crosstalk.

Accordingly in this work, three sub-problems are identified for IRA-RWA: 1) *reachability graph computation (RGC) based on approximate linear additive model (ALAO) model:* computes the RG of the physical network considering ALAO models (see next subsection) for PLIs; assists in improving the RCP; 2) *route computation phase (RCP):* computes the most likely feasible routes either on the physical network or RG including the regenerator selection; tries to reduce the number of setup attempts; and 3) *signaling phase:* the mechanisms used to signal and provision the feasible path given by RCP; validates the optical feasibility of new LSP considering exact PLIs models and checks the impact of new LSP on active LSPs to avoid potential active LSP disruption. All these three phases are explained in detail in the next subsections.

B. *Reachability Graph Computation (RGC) Phase*

The RG contains all network nodes and a new set of links between network nodes and regenerator nodes that are transparently reachable. In order to evaluate the reachability, we use ALAO model which uses the following information: optical power, OSNR, amplifier spontaneous emission (ASE) noise, chromatic dispersion (CD), and polarization mode dispersion (PMD). The ASE noise introduced by an amplifier is evaluated using $ASE_{amp} = G_{amp} + 10\ log_{10}(hvB) + NF_{amp}(G_{amp})$, where ASE_{amp} is the amplifier noise in *dBm*, G_{amp} is the amplifier gain in *dB*, *hvB* is physical constant [3], and $NF_{amp}(.)$ is the amplifier noise figure which is function of amplifier gain. The noise to signal ratio (NSR) of an optical amplifier is given by $NSR_{amp} = ASE_{amp} - P_{out,}$ where, P_{out} is the output power of amplifier. The total link (path) NSR is the linear sum of each amplifier NSR along the link (path) and is given by $NSR_{link} = 10\ log_{10}(\Sigma 10^{(NSR/10)})$. Optical power in *dBm* is the egress link pre-amplifier optical output power. CD of the link is the total CD including the dispersion compensation units (DCUs) contribution. CD of the path is the linear sum of CD of all links in the transparent segment. PMD of the transparent segment is the sum of PMD of all the links. The models used for computation of CD and PMD can be found in [1]. OSNR of the path is $OSNR = -\ NSR$, where OSNR is the channel OSNR. The feasibility of the reachability link is evaluated for all transponder classes (i.e., *10* vs *40 Gbs*; FEC vs no FEC) by validating the channel OSNR (including additional OSNR penalty as described later) with respect to the transponder min. OSNR threshold and the channel CD/PMD with respect to the transponder sensitivity. Finally, the list of feasible supported transponder classes is associated to each reachability link.

In RGC phase each node builds its reachability map (RM) which contains the node itself and the regenerator nodes that are transparently reachable from it. To build the RM of a node, physical links are assigned a weight based on ASE noise on the link; then it computes the shortest path to all the regenerator nodes. Next, if the shortest path is optically feasible with respect to ALAO model (described earlier), then a reachability link is created in the RM; otherwise no corresponding reachability link is created. To evaluate the optical feasibility of reachability links, each node in the network must have the following information: 1) link ASE noise and ALAO model parameters used in computation of RM, which are disseminated via extended OSPF-TE; and 2) optical feasibility constraints, which can be pre-configured as it is static information. The RM of each node is disseminated to all other nodes in the network using extended OSPF-TE (Section III.E), which in turn are used to construct the overall RG. The RM information is managed in the traffic engineering database (TED). The additional information stored in TED consists: 1) *link optical parameters:* ALAO optical parameters related to the physical links; 2) *reachability link description:* the reachability links between two end points.

ALAO model used in RGC is not accurate as: 1) only single-channel linear effects are considered and 2) real model of some of the PLIs is not linear/additive (e.g., SPM). Hence, to account for errors in ALAO model, we consider additional OSNR penalty in the feasibility evaluation of reachability links. The additional OSNR penalty can be *fixed* or *adaptive* [18]. In this paper we use fixed additional OSNR penalty of 1.5 dB [18], which is selected based on extensive experimental studies on the network topologies used in simulations. Note that, though we use ALAO model in the RGC, we consider exact PLIs models and NLIs (e.g. multi-channel effects) while validating the optical feasibility of the path during the SP (Section III.D). The main advantages of using ALAO model in RGC are: 1) less control plane overhead as ALAO model requires only limited PLI and reachability links information through OSPF-TE extensions; 2) less computational complexity, allowing for on-the-fly computation of RM and end-to-end loose hop routes; and 3) lower setup time, as ALAO model provides most likely feasible paths (compared to simple crank-back on the shortest path [13-16]) and hence reduces additional setup attempts.

C. Route Computation Phase

When there is a LSP request, the source node tries to find *k*-transparent feasible paths with respect to ALAO model on the physical network. If a transparent path exists, then it starts signaling on the transparent path, which validates the feasibility using the exact PLIs and also checks whether it disrupts any active LSPs using mechanism in [3]. If there is no transparent path or the number of attempts is more than a threshold (K_t), then the source node computes a feasible shortest path on the RG. For the purposes of finding the route on RG, the regenerator sites without available regenerators are pruned from the RG. The shortest path on the RG is an end-to-end loose hop route (called E-LSP) identifying the selected regenerator sites as fixed nodes along the path. Fig. 1 shows the flow chart of RCP. Fig. 2 describes the overall process of setting up an E-LSP. The E-LSP consisting of multiple transparent segments (called S-LSPs) is signaled using RSVP-TE loose-route explicit route object (ERO). The full explicit route of each S-LSP is evaluated by the loose-hop ingress node using K-SEQ approach [3]. If there is a failure in S-LSP (e.g., due to potential active LSP disruption, etc.,) an alternate route is computed. In case of failures in the signaling of E-LSP (e.g. no alternate routes available for an S-LSP, etc.,); the next candidate E-LSP route is computed on the RG, i.e., a global crank-back using K-SEQ approach up to K_r attempts. It is important to note that, if the LSP is routed on RG, it is possible that the lightpath could travel through the same link twice, but in that case different wavelength is used on different reachability links.

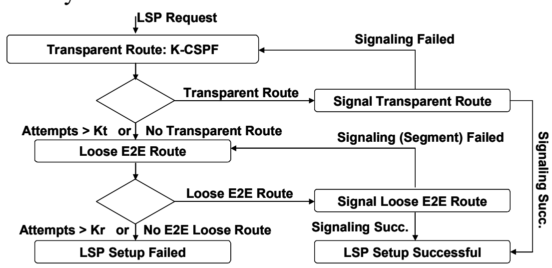

Fig 1. Flow chart of the first two steps in route computation.

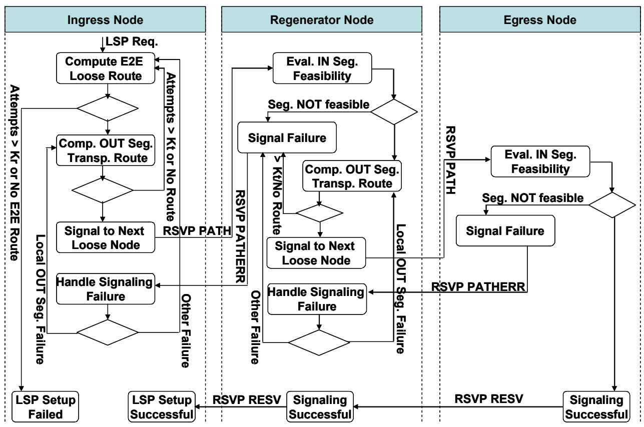

Fig 2. Flow chart of route computation and signaling phases.

D. Signaling Phase and Optical Feasibility Validation

The timing diagram for setup of an E-LSP is shown in Fig. 3. If there exists a transparent path the first regenerator node must be considered as the destination node in Fig. 3 and the following explanation. When there is an LSP request, the source node requests local CSPF to compute a transparent path to the destination node (*step 3*). If there exists a transparent path, the source node sends a *PATH* message (*step 4*). All intermediate nodes update the optical parameters of signaled wavelengths considering wavelength continuity constraint. When the *PATH* message reaches the destination node, it 1) validates the optical feasibility using exact PLIs model; and 2) checks no active LSP is disrupted (*step 5*). If at least one wavelength is optically feasible and does not disrupt any active LSPs, the upstream LSP signaling is started with a full strict route (*steps 6-7*). If the upstream setup (*step 8*) succeeds, the *RESV* phase for the downstream is carried out (*step 9*). If the transparent path setup is successful, the LSP is considered as accepted and the process terminates. If the transparent path setup is not successful or if it does not exist, an E-LSP is computed on the RG. If there is no E-LSP, the request is failed and the process terminates; otherwise RSVP-TE starts the signaling on E-LSP using LSP stitching mechanism [5].

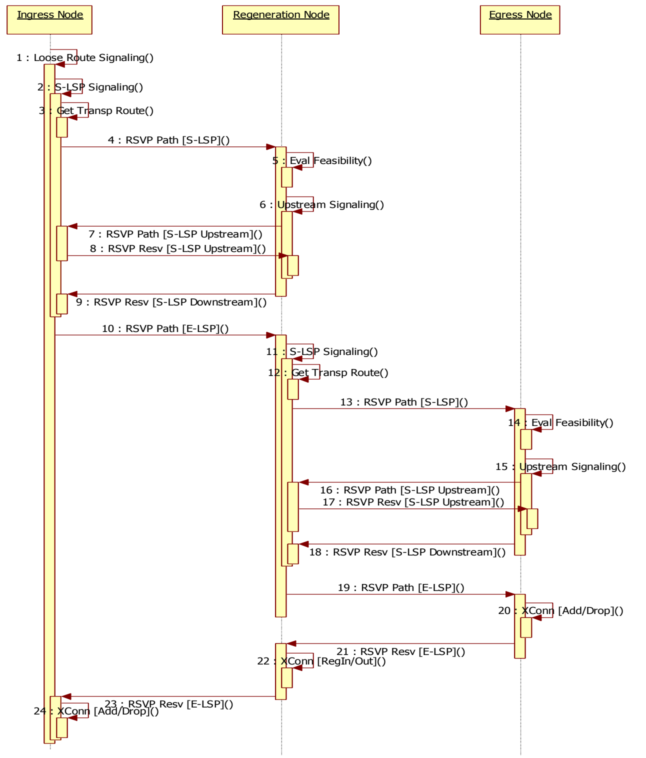

Fig 3. Timing diagram of S-LSP or E-LSP setup.

To signal E-LSP, a new S-LSP instance is created for each loose hop segment and managed independently using the process as explained earlier. When the *RESV* phase for the first S-LSP is finished, the ingress node sends *PATH* message (for E-LSP) to the next S-LSP ingress node (*step 10*). The whole procedure is repeated for all S-LSPs as shown in *steps 11-19*. Finally, when the *PATH* message (for E-LSP) reaches the destination node, a *RESV* message (for E-LSP) is sent, which stitches all S-LSPs to form an E-LSP (*steps 20-24*). During the *RESV* message processing, intermediate nodes will configure OXCs and allocates the regenerators at the selected regenerator sites for E-LSP. When the *RESV* message reaches the source node, the LSP setup process terminates.

E. Extensions to OSPF-TE and RSVP-TE protocols

OSPF-TE is extended to disseminate regenerator and wavelength availability, PLIs required by ALAO model, and reachability links. The wavelength availability information is encoded in new sub-TLV of link TLV [19]. The regenerator type/class, number of regenerators accessible from ingress port, optional list of egress ports bound to the regenerators (not required for directionless architectures), is encoded in router LSA. For this purpose, an opaque LSA type or a TE LSA TLV type needs to be defined as it is not defined in [20].

The PLIs information required by ALAO model is encoded in link TE LSA instance [20] using additional sub-TLV containing: ASE, egress optical power, CD, and PMD. The reachability links are flooded as additional node interfaces (i.e., link TE LSA instances). Additional sub-TLV is defined for the list of optical costs of reachability links for different transponder types. Note that the reachability links are different for different transponder type. The description of the reachability links as standard point-to-point links allows the CSPF to prune reachability links based on the *color/administrative group* attribute. In our earlier work [3, 21] we have defined extensions to RSVP-TE to carry PLIs information for IA-RWA in transparent networks. In LSP stitching, each S-LSP is managed independently; hence, no additional extensions are required. However, note that each S-LSP has to verify independently the optical feasibility and the effect of each S-LSP on the active LSPs.

IV. PERFORMANCE STUDY

In this section, we present the simulation environment, network, and traffic scenarios used in simulation experiments. Several modifications are made to standard OSPF-TE on GMPLS lightwave agile switching simulator (GLASS) [22]. The results are collected with target accuracy of *0.05* and confidence level of *95%*. RG is constructed using the ALAO model. LIs and NLIs have been modeled using specific mathematical models described in [1] and [3], respectively. *K-SEQ* approach [3] together with RSVP-TE extensions for LSP stitching mechanism [5] has been implemented in GLASS. The maximum number of tries for S-LSP (K_l) is set to *3*, while for E-LSP (K_r) is set to *6*. We have used fixed OSNR penalty of *1.5 dB*. As existing mechanisms do not handle potential active LSP disruption which is very important [3], in this section we present results only for our proposed approach.

A. Network and Traffic Scenarios

Extensive simulation experiments are run on a set of regular/irregular topologies, and real-world networks from our clients. However, due to space constraints, we present the results only for typical USA long-haul network [23] in Fig. 4 (scaled down by a factor of *1.5* to avoid having regenerators at both ends of some links). Each link has two unidirectional true-wave classic (TWC) fibers. The optical line amplifiers are placed at equidistant with a condition that the maximum span length is not more than *80 Km*. Optical amplifiers are based on Erbium-doped fiber amplifier (EDFA) technology. CD is compensated through dispersion compensation unit (DCU). System supporting *40* wavelengths in *Band C* is equipped with a pre-amplifier with output power of *1.0 dBm*, a pre-DCU with *100 ps* for TWC fiber, and a booster amplifier with output power of *-1 dBm* is used. OXCs are equipped with *10G* transponders with EFEC that allow maximum transparent reach of *1250 Km.* The regenerators are placed using algorithm in [17] at nodes shown in red color and there is no limit on the number of regenerators. Other optical parameters are listed in Table. I.

The dynamic traffic scenario used in the experiments consists of LSP requests with Poisson arrivals at an average rate $1/\mu$ (with $\mu = 2\ sec$) per second. An installed LSP has an average exponential duration of $\nu\ sec$. The traffic requests are uniformly distributed among all nodes. The traffic load β is defined as the average wavelength usage computed in percent as: $\beta = (N_c \times L_c)/(M \times W) \times 100\%$, where N_c is the average number of active LSPs and equals ν/μ, L_c is the average number of hops in the network considering only shortest paths between all pairs of nodes, M is the number of links and W is the number of wavelengths in each link.

TABLE I: OPTICAL PARAMETERS USED IN SIMULATIONS

Description	Value	Unit
Output Power of Transmitter	*0*	*dBm*
Loss of Fiber	*0.25*	*dB/km*
Channel Add Loss	*8*	*dB*
Channel Drop Loss	*14.3*	*dB*
Channel Pass-through Loss	*12.9*	*dB*
Noise Figure of EDFA	*5.8*	
Reference Wavelength	*1545.32*	*nm*
CD of TWCF at Reference Wavelength	*2.03*	*ps/nm/km*
Slope Factor of CD of TWCF	*0.07*	$ps/nm^2/km$
PMD of TWCF	*0.1*	$ps/\sqrt{km}$
PMD of Optical Amplifier	*0.3*	*ps*
PMD of Optical Nodes	*0.25*	*ps*
Crosstalk Ratio of Optical Nodes	*-35*	*dB*

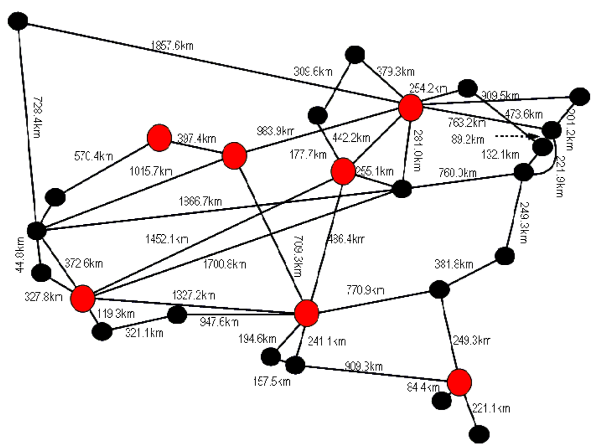

Fig 4. Typical USA long-haul network topology [23].

B. *Performance Metrics*

Three performance metrics have been used for comparison:

Blocking Probability (BP): The ratio of the number of rejected LSPs to all requested LSPs. Two main contributions to BP are: S-LSP blocking and E-LSP blocking. S-LSP blocking is due to 1) unavailable resources, e.g. wavelengths and 2) blocking due to unfeasibility of S-LSP, e.g. LI unfeasibility or NLI unfeasibility or affected LSP unfeasibility. E-LSP blocking is due to 1) S-LSP failure, e.g. S-LSP downstream or upstream failure or reservation failure.

Average Number of Setup Attempts: Average number of setup attempts over all successful LSPs. It is evaluated at a) E-LSP level: the number of alternate E-LSPs attempted and b) at S-LSP level: S-LSP setup attempts.

Additional Resources: Average number of additional S-LSPs (regenerators) required on the selected path with respect to the shortest path and is evaluated over all successful LSPs.

C. *Results and Discussion*

USA long-haul network [23] is an average size network in which *~60%* and *38%* paths requires only *1* and *2* regenerators on the shortest path, respectively. In the following results, 1) 'Seg-1', 'Seg-2', and 'Seg-3', are the blocking for E-LSPs with no, one, and two regenerators, respectively, on the shortest path; and 2) 'All' is the average over all accepted E-LSPs. As shown in Fig. 5 BP increases as the load increases, due to increase in the effect of PLIs and wavelength unavailability. As wavelength availability information is disseminated using extended OSPF-TE, the wavelength blocking is zero as shown in Fig. 6. The higher blocking due to a) NLIs and b) potential active LSP disruption, show how the ALAO model accuracy changes with the load. It fails to find a feasible path in the limited number of E-LSP attempts at higher loads as the multi-channel effects are not considered in ALAO. As expected the BP for the transparent paths (Seg-1) is lower than the paths with two or three S-LSPs, due to the BP contribution from each S-LSP.

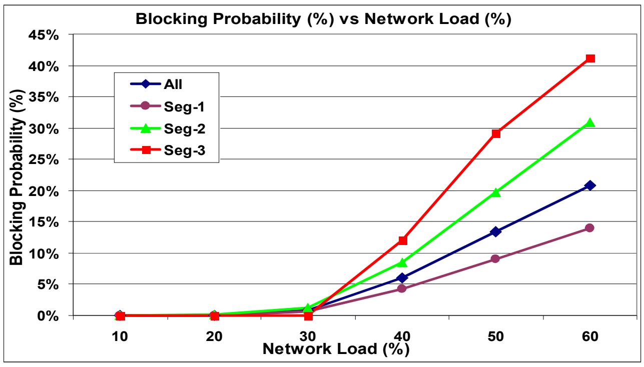

Fig 5. BP of E-LSP with different number of segments vs. network load.

Fig. 6 shows the blocking due to various contributions. At lower loads, BP due to LIs is low, but it increases with load due to the increase in inaccuracy of CD in ALAO model, as it considers the average CD for the reference wavelength. However CD varies widely with respect to reference wavelength depending on CD coefficient slope and is not the avg. value, hence results in higher blocking. Blocking due to affected LSP and NLIs depends on the number of active LSPs and their distribution in the network due to inherent nature of NLIs. The affected LSP blocking (which is around *2%* to *8%*) shows the percentage of LSPs that are blocked due to potential active LSP disruption. *That means existing approaches [12-16], that did not implement a mechanism to handle potential active LSP disruption will disrupt 2% to 8% of active LSPs.*

As ALAO model is an approximate model, the RG computed may not be very accurate (and hence the E-LSP computed on the RG) in terms of actual feasibility. Hence, finding a feasible E-LSP might need more than one attempt as shown in Fig. 7. The number of attempts shows how close the ALAO model is to the actual PLI and feasibility. As expected the paths that require higher number of regenerators require more attempts compared to the paths that require less number of regenerators. As ALAO model requires only limited PLIs information, it provides a good trade-off between control plane overhead and setup time.

The average number of additional regenerators required with respect to the shortest path increases with the load as shown in Fig. 8. This is due to the fact that shortest path may not be feasible due to PLIs or wavelength unavailability requiring several attempts with more regenerators. However, as the number of tries on the RG is limited to *6* too long paths are not tried, which is the reason for lower additional number of regenerators required in case of paths with three segments.

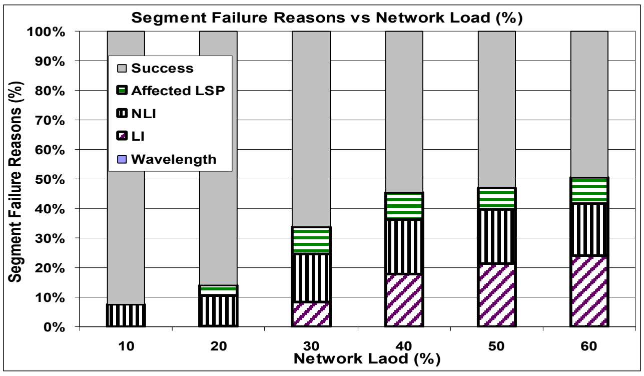

Fig 6. Segment failure reasons vs. network load.

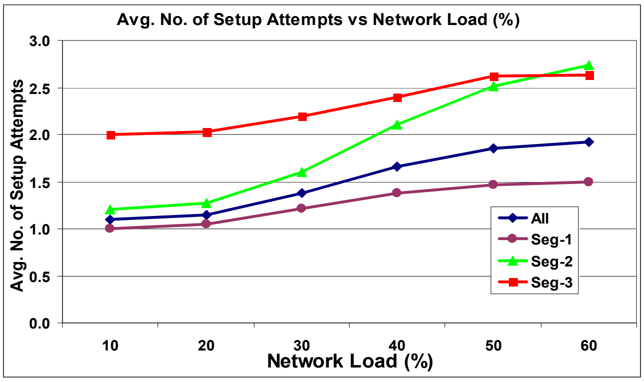

Fig 7. Average number of E-LSP setup attempts vs network load.

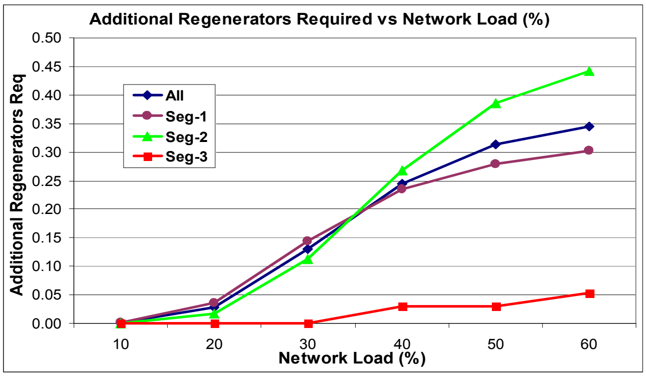

Fig 8. Average additional regenerators required vs. network load.

V. Conclusions

In this paper, we presented a novel three phase approach for IRA-RWA in translucent optical networks. The proposed approach tries to minimize regenerator/wavelength usage and the number setup attempts. The proposed hybrid OCP approach extends OSPF-TE to disseminate PLIs information required for constructing RG and wavelength/regenerator/reachability link availability information. Whereas, RSVP-TE is extended to carry full PLIs information required for optical feasibility validation and to avoid potential active LSP disruption. Extensive simulation experiments are conducted on several network topologies. The simulation results show that the proposed approach provides a good trade-off between blocking and number of setup attempts. We demonstrated that the proposed approach is feasible to implement and is ready for deployment in real-world optical networks.

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