Estimating QoT of Unestablished Lightpaths

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Abstract: We develop a framework to estimate the Quality of Transmission (QoT) of unestablished lightpaths considering interference effects. Accurate estimations combined with lightpath provisioning close to current network state can yield significant savings in regenerators.

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1. Introduction

In transport optical networks the optical signals can transparently pass intermediate nodes and traverse long links. The accumulated impairments may degrade the signal, making its Quality of Transmission (QoT) unacceptable and necessitating the use of regenerators at intermediate hops. Traditional provisioning of lightpaths requires the use of abundant margins on the optical reach to avoid subsequent interventions in these channels during the network lifetime, despite increased interference due to new lightpaths (the utilization of the network is light at the beginning of its life, and increases as more connections are established), equipment ageing, maintenance operations (e.g., additional connectors, fixing a fiber cut), or other events. These margins often force the deployment of regenerators or more robust transponders which during the set-up are not strictly necessary. In such a system, QoT monitoring is used to check lightpaths after set-up to verify that the design margins were safely applied. Clearly, provisioning with lower margins would be desirable [1], as it can postpone or completely avoid the purchase of equipment. This, however, requires new mechanisms that would rely on physical layer monitors to (i) observe and take into account the actual state of the network when provisioning new lightpaths, and (ii) anticipate, identify and remedy the problems that could occur at later times due to such initial choices. ORCHESTRA [2] extends coherent receivers to operate as optical performance monitors (OPM) and develops an accurate and responsive monitoring and control plane to serve these aforementioned needs.

In this context, in this paper we assume that OPM monitoring information is available and propose a way to use that in optimization decisions, so as to increase the network efficiency and operate it closer to the current conditions. More specifically, we develop a framework that correlates monitoring information from active lightpaths to estimate a) the QoT of a new lightpath before it is established, and b) the degradation the new lightpath will cause to existing ones, taking into account the interference of spectrum-neighboring channels. The estimation that our framework provides is more accurate than previous approaches [3,4], which made worst case assumptions for interference, assuming that all channels are simultaneously lighted to obtain a pessimistic QoT that did not reflect the current network state. Also, as an extension to [3,4] that targeted 10 Gbps WDM networks, we follow the technology trends and consider multi-rate WDM, targeting as a next step to generalize the framework for elastic networks.

2. Network model and QoT estimation framework

We assume an optical transport network that is enriched with OPM capabilities. Note that coherent receivers deployed today are packed with DSP capabilities, so they can be extended, almost for free, to function as OPMs [2]. We assume that the DSP at the receivers performs ideal electronic dispersion compensation and MIMO equalization, and that span loss is exactly compensated by span amplification. We consider that an OPM (receiver) can provide information about the OSNR of the lightpath that takes into account both ASE (Amplified Spontaneous Emission) and NLI (Non linear interference) or separate information for these, and that BER can be calculated based on those values. Following assumptions based on the GN model [5] we assume in our estimation framework that the inverse of OSNR is additive per link. In our simulations we use the GN model as the ground truth for validating the accuracy of our framework; the framework itself does not depend on the GN model for calculating any parameter, in a real system values provided by OPMs will be used. However, it assumes the additive property to hold for the estimated parameter or parameters that comprise it, which was shown to be accurate according to the GN model.

In the network we assume that there is no wavelength conversion and thus the wavelength continuity constraint holds for each lightpath. For long connections regenerators are placed, and each segment between regenerators is considered a separate lightpath that can use a different wavelength. Monitors are located at the termination point of each lightpath (receiver). The choice for a new lightpath (path and wavelength to use) is taken by a Routing and Wavelength Assignment (RWA) algorithm that utilizes our QoT estimation framework.

We now formally define our QoT estimation framework. We go through the basic network algebraic representation and then describe how we can estimate the QoT of an unknown lightpath using the QoT data of

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established ones. Consider a network with K nodes, L unidirectional fiber links and M already established lightpaths in it. The routing matrix of established lightpaths is defined as $G\in\{0,1\}^{MxL}$ where $G_{m,l}=1$ when a lightpath m contains link l. Consider the end-to-end parameters $\mathbf{y}\in\mathbb{R}^M$, where y_m is a value for lightpath m. Vector $\mathbf{y}$ can be written as linear combination of link-level vector parameters $\mathbf{x}\in\mathbb{R}^L$ so that $\mathbf{y}=G\mathbf{x}$. We denote by $\mathbf{y_m}$ (or $\mathbf{y_n}$) the parameters of the lightpaths for which monitoring data are available (or should be estimated), and set $\boldsymbol{y}=[\boldsymbol{y}_m^T,\boldsymbol{y}_n^T]^T$. Similarly, the routing matrix G is denoted as $G=[G_m^T,G_n^T]^T$ where G_m (or G_n) includes the rows that correspond to lightpaths for which monitoring information is available (or whose QoT parameters we want to estimate). Then, $[\boldsymbol{y}_m^T,\boldsymbol{y}_n^T]^T=[G_m^T,G_n^T]^T\mathbf{x}$. The objective is to determine the unknown end-to-end parameters $\mathbf{y}_n$, where $\mathbf{y}_n=G_n\mathbf{x}$. This can be achieved using Network Kriging (NK) or Norm Minimization (NM) [3,4]. The key idea behind NK is that the best (mean-square error) linear estimate of $\mathbf{y}_n$ is: $\hat{\mathbf{y}}_n=G_nG_m^T\left(G_mG_m^T\right)^+\mathbf{y}_m$, where $(.)^+$ denotes a pseudo-inverse. NK complexity is $O(M^3)$. NM estimates $\mathbf{x}$, which is then used to derive $\mathbf{y_n}$. The respective problem is defined as: $\min\limits_{x,r}\|\mathbf{r}\|_2^2+\|\mathbf{x}\|_2^2$, subject to $G_m\mathbf{x}+D_2\mathbf{r}=\mathbf{y}_m, x\geq 0$, where $\mathbf{r}$ is a regularization parameter and D_2 is positive-definite diagonal matrix, with small values (10^{-4}) to satisfy the constraints with reasonable accuracy. This problem can be solved using software packages such as PDCO [6], with complexity $O(\alpha|L|^3)$, where α is a measure of the requested estimation accuracy and $|L|$ is the number of links.

2.1. Interference Aware Estimation

The previous problem statement is generic and can be modified to estimate interference effects from spectrum neighboring channels. This will yield extra accuracy and consequent efficiency benefits, enabling a cross-layer optimized network, as opposed to making worst case assumption that all channels are lighted (done in [3, 4]). To model neighbor interference, we define an interference aware (IA-) transformed graph *G'* from the original graph *G*. In the example of Fig.1a we assume that only a direct neighbor (from either side) of a wavelength causes interference. On the first link, lightpath using λ2 has two neighbors, one from each side (λ1 and λ3), λ1 has one neighbor (λ2), and λ3 has one neighbor (λ2). In the IA-graph *G'* of Fig. 1b, each link is replaced by three links (called *IA-links*), representing the three cases: (1) no neighbors, (2) one neighbor from one side (not distinguishing the side), and (3) two neighbors. At each hop in *G'* we route a lightpath over the appropriate IA-link according to the number of active neighbors in *G*. Lightpaths in *G* with the same number of active neighbors on a link are assumed to suffer equal interference and are routed over the same IA-link in *G'*, as done for λ1 and λ3 in the first link. This holds (with small error) when neighboring lightpaths have the same launch power and baud rate. The above description of the auxiliary graph *G'* can be easily modified to model the interference from more distant neighbors and more baud-rates by introducing more IA links in *G'* (omitted for brevity). In practice, modeling the interference from the two neighbors (which contribute the most) is adequate to obtain good QoT estimates. To keep the number of IA-links in *G'* low (neglect distant neighbors and similar baud-rates), relaxed grouping criteria and small margins following certain worst case assumptions can be applied.

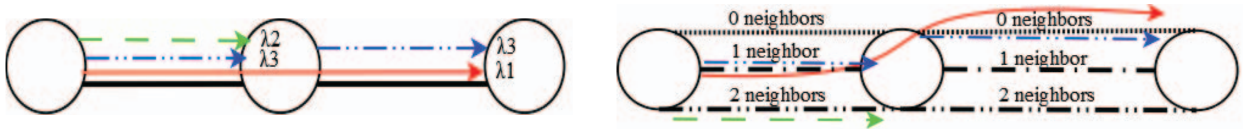

Fig. 1 (a) The initial network graph G, (b) the auxiliary IA-network graph G' and its IA-links.

To estimate the QoT of a new lightpath we use the auxiliary IA-graph and we construct G_m (we suppress the prime in *G'* since from now on we will only deal with auxiliary IA-graphs) without considering the lightpath to be established. The columns of G_m correspond to IA-links, modeling the number of neighboring lightpaths. Vector $\mathbf{y}_m$ represents the monitored impairments (the inverse of OSNR is used). When we route the new IA-lightpath in the auxiliary IA-graph, we find the kind of neighbors it would have if it was accepted in the network and this is used to create G_n. In case the new lightpath crosses an IA-link not used by any previous lightpath (not a column in G_m), to be safe we follow a worst case approach and route it over an IA-link with more neighbors. Then, NK or NM algorithm is used to calculate the QoT of the new lightpath. For estimating the effect the new lightpath p will have on existing ones, matrix G_m is again constructed without considering p, and $\mathbf{y}_m$ are the monitored impairments. Matrix G_n is created to contain the lightpaths that are affected if p is established. These lightpaths actually exist in G_m but for creating G_n they are rerouted in the IA-graph assuming that the new lightpath is established, and thus they cross some higher interference links. Using such input our estimation framework evaluates whether establishing the new lightpath makes infeasible some existing ones.

The estimation frameworks are enhanced by adding a database (DB) that stores all the past measurements as a way to enrich G_m. Aging effects can be considered by removing entries after a certain period. The technical details concerning the integration of the database with the control plane of the network are outside the scope of this paper.

3. Simulations

We evaluated the performance of our proposed framework using simulation experiments. We used the NSFNET topology consisting of 14 nodes and 22 bidirectional links, with link lengths taken to be the Euclidean distances multiplied by 1.2. The fiber types were assumed to be SSMF with attenuation coefficient 0.25 dB/km, dispersion parameter 16.7 ps/nm/km, and nonlinear coefficient 1.3 1/W/km. The span length was set at 100 km and EDFA noise figure to 6 dB. We consider two different transmission configurations: the first assumes 100G PM-QPSK with 28 Gbaud and the second assumes transmissions at the same rate/format but at both 28 and 32Gbaud. Lightpath request arrivals follow a Poisson process of rate λ, demand durations are exponentially distributed with mean $1/\mu$, and source and destination are uniformly chosen among the nodes. Each new lightpath request is served by a simple RWA algorithm, using the shortest path and the first-fit wavelength assignment policy.

Fig. 2 shows the accuracy of our estimation framework using the Mean Squared Error (MSE) for $log(BER)$ as a function of the number of IA-lightpaths available in the database (DB). Network kriging (NK) and norm minimization (NM) were found to provide almost identical results, the NM providing slightly more accurate solutions, and thus it is the one used in the following. The time required to obtain the IA-graph and calculate the estimates was 0.9s for 300 IA-lightpaths on an i5 CPU. In Fig. 3 we observe that when the number of IA-lightpaths in the DB is low, the MSE is high. In most cases the estimation accuracy is between 0.01 and 0.5 dB. The difference was large in single link lightpaths, which usually have very low BER, making such inaccuracy insignificant in practice. To show this, in Fig. 3 we also depict the MSE for lightpaths consisting of at least two links. To achieve a negligible MSE (less than 0.05) the DB must have around 600 IA lightpaths (which translates to approximately 170 lightpaths in the original network) for the single baud-rate and around 1000 (250 lightpaths) for the dual baud-rate network. Note that the DB is filled up very quickly, since we store information for the IA-links for each lightpath and therefore a single lightpath may occupy multiple database entries. Whenever a new lightpath is inserted, it triggers multiple DB entries since it affects all its close neighbors and therefore their IA-links. Active lightpaths (not carrying data) can improve the estimation accuracy when the DB is sparse, but this is left for future work.

We also calculated the regenerator savings that our estimation framework can achieve. Regenerators are placed when a lightpath has high BER (larger than 10^{-2} before FEC). We use a 0.1 dB margin to account for the estimation error in our framework. Our proposed framework is also used to estimate the degradation a new lightpath causes to existing lightpaths: we search for an alternative wavelength in case that it turns unacceptable an existing one. We compare our framework to (i) worst case assumption (all channels lighted) and (ii) BER values obtained from the GN model (referred to as *real*). Fig. 3 shows saving on the maximum number of regenerator in the network of up to 47% for our approach when compared to the worst case assumption, exploiting savings of up to $4\cdot10^{-2}$ in BER, while it uses less than 5% more regenerators than the real case, where we accurately know the BER. In Fig. 4 we present the maximum regenerators used in a single node, where we observe similar savings.

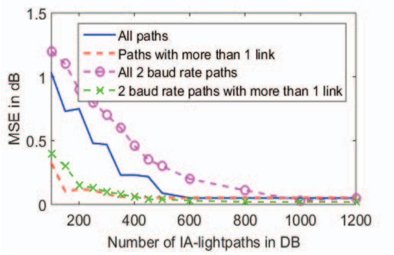

Fig. 2 Mean Squared Error (MSE)

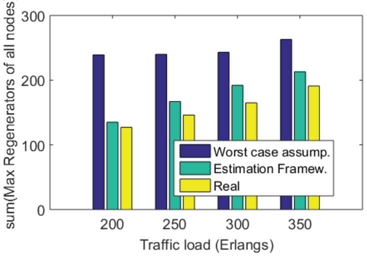

Fig. 3 Total number of max. regens of all nodes

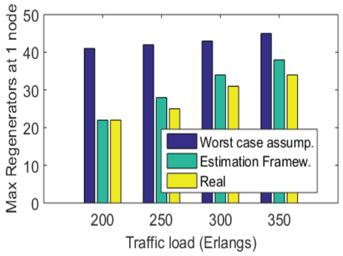

Fig. 4 Max. number of regens of a node

4. Conclusion

We presented a framework for estimating (i) the QoT of unestablished lightpaths and (ii) their effect on established ones, taking into account interference effects. Our framework achieved low MSE and up to 4.10^{-2} more accurate BER estimations compared to using a worst case interference assumption. This can be translated to significant regenerator savings, using a baseline algorithm that provisiones lightpaths close to the current network state.

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5. References

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