Improving QoT Estimation Accuracy through Active Monitoring

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ABSTRACT
Estimating the Quality of Transmission (QoT) of lightpaths is crucial for reducing provisioned margins, making optimized dynamic decisions, and localizing failures. We leverage a QoT estimation tool that uses feedback from the network in order to provide accurate QoT estimations. We propose a scheme to establish active monitoring lightpaths (i.e., probe lightpaths used only for monitoring purposes) in order to improve the QoT estimation accuracy.

Keywords: Active monitoring lightpaths, QoT estimation, estimation accuracy, physical layer margins.

1. INTRODUCTION

In transport optical networks optical signals traverse long links and accumulate physical layer impairments (PLIs). PLIs degrade the Quality of Transmission (QoT) of the lightpaths and can turn it unacceptable, necessitating the use of regenerators at intermediate nodes. Accurate QoT monitoring and estimation are very important features that can enable both the reduction of provisioning margins and a more dynamic and efficient network operation.

Traditional network planning requires the use of abundant margins [1] (also referred to as power budgets) to guarantee an acceptable QoT for all the lightpaths until the End of Life (EoL) of the network. The QoT of an established lightpath decreases as time passes, due to increased interference from new lightpaths, equipment ageing and maintenance operations such using splices to fix a fiber cut. The margins employed to compensate for these degradations often force the deployment of expensive regenerators that are not strictly necessary during the initial set-up. Lower margins can result in significant benefits [1][2][3] since the purchase of equipment can be avoided or postponed, thereby reducing the total network costs. Lowering the margins, however, requires new networking mechanisms based on optical performance monitors (OPM), to observe the state of the network and (i) accurately estimate the QoT before provisioning new lightpaths, and (ii) anticipate, identify and fix the QoT problems that may arise [4][5][6].

Moreover, optical networks are becoming more dynamic, with the advent of flex-grid and configurable transceivers [7]. In Elastic Optical Networks (EONs) the reconfiguration actions benefit from accurate QoT estimation. For example in a network that automatically adapts to traffic changes, accurate QoT estimation is required in order to estimate the connection feasibility and quantify the impact of the adapted transmission parameters (e.g. spectrum, modulation format).

During the past few years, optical coherent transceivers are being installed in core networks and it is taken for granted that we are moving towards all-coherent networks. Such transceivers employ DSP processing at the receivers and are able to monitor and compensate certain impairments such as chromatic dispersion. ORCHESTRA project [8] proposes to extend these coherent receivers to operate as OPM and develops an accurate and responsive monitoring and control plane to support and use such data. It also develops QoT estimation models [9], [10] that take feedback from the coherent receivers to increase the estimation accuracy, reduce the margins and enable efficient dynamic network operation.

In this paper we leverage the feedback based QoT estimation tool presented in [9] and we propose a scheme to establish *active monitoring lightpaths* (probe lightpaths used only for monitoring purposes) in order to further improve its estimation accuracy. The algorithm takes into account the current network state (i.e. the established lightpaths) and decides which active monitoring lightpaths and in what order to establish so as to acquire new information for links that are not sufficiently monitored.

2. NETWORK SCENARIO

We assume an optical transport network that employs either fixed - (WDM) or flex (elastic) -grid [7]. The nodes are connected through uncompensated fiber links, each consisting of a number of fiber spans terminating at an amplifier that compensates exactly the loss of the span. We assume that there is no wavelength conversion and thus the wavelength (or spectrum, in the case of a flex-grid network) continuity constraint must hold for a lightpath that crosses several links.

The ORCHESTRA project envisions nodes equipped with coherent transceivers with DSP capabilities that can be programmed to function as software defined optical performance monitors (soft-OPMs). A soft-OPM at a receiver provides aggregate measures over a path that usually traverses several fiber spans and links. ORCHESTRA's optimization engine uses (space and spectrum) correlation algorithms to combine information from multiple soft-OPMs throughout the network in order to provide, among others, accurate quality of transmission (QoT) estimation and detection of failures.

Estimating the QoT of new lightpaths is a fundamental functionality that is typically performed by a "Q-tool" when planning or upgrading the network. QoT estimation methods range from very complex (Schrödinger equations) to simulations and analytical models of lower complexity (e.g. GN model [11]). Such models require accurate knowledge of the physical layer parameters. Since it is not possible to have accurate knowledge, margins are used to account for the inaccuracies, equipment ageing-failures and increased interference as the load increases with time. In ORCHESTRA, we rely on information obtained by the receivers (soft-OPM) and correlate it to obtain accurate estimates of the physical layer. This can be used to replace or feed the Q-tool with better parameters.

In particular, we consider a network $G=(V,E)$ where V denotes the set of nodes and E the set of unidirectional fiber links. The routing matrix of the established lightpaths is defined as the binary matrix $R_M \in \{0,1\}^{|M|\times|E|}$, where $R_M[m,l]=1$ when lightpath m contains link l, and is 0, otherwise. Consider the end-to-end vector of parameters $\mathbf{y}_M \in \mathbb{R}^{|M|}$, with y_m member of $\mathbf{y}_M$ representing the value of lightpath m. Vector $\mathbf{y}_M$ can be written as a linear combination of link-level vector parameters $\mathbf{x} \in \mathbb{R}^{|E|}$ so that $\mathbf{y}_M = R_M\mathbf{x}$. We assume that we want to estimate the end-to-end parameters of a set N of new lightpaths, denoted by vector $\mathbf{y}_N \in \mathbb{R}^N$, assuming that we know their routing $R_N \in \{0,1\}^{|N|\times|E|}$. Then, we have

$$\mathbf{y} = \begin{bmatrix} \mathbf{y}_M \\ \mathbf{y}_N \end{bmatrix} = \begin{bmatrix} R_M \\ R_N \end{bmatrix} \mathbf{x} \tag{1}$$

The impairment values in vector $\mathbf{y}$ can be different for different use cases. Assuming that we want to estimate the QoT, we assume $\mathbf{y}_M$ to be the inverse of SNR of the established paths. We estimate the inverse of SNR of the new lightpath $\mathbf{y}_N$, from which assuming known modulation format and FEC, we can calculate the BER (considered the ultimate QoT estimation metric). Estimating $\mathbf{y}_N$ in this formulation can be done with Network Kriging **Error! Reference source not found.**.

The above definition of matrix R depends only on paths and is thus able to convey information only on space dependencies, while it ignores spectrum dependencies. To account for interference and the actual current load of the network, and thus obtain higher QoT accuracy, we extend the above model to also exploit correlations in the spectrum domain. We define an interference aware (IA-) transformed graph G' in which each link in G is replaced by a *set* of IA-links in G' which represent the number, position and connection attributes (e.g. baud rate, power) of the active neighbors on each link. The underlying assumption is that lightpaths with the same relative position of active spectral neighbors and the same connection attributes exhibit similar interference. We then route the lightpaths over the expanded graph G', according to the neighbors that they have in each link, and obtain the new routing-spectrum matrix R_M, recording correlations in both space and spectrum (i.e., between lightpaths sharing the same IA-links) Using this routing matrix in the formulation of Eq. (1) we obtain QoT estimates that account for actual interference [9].

The proposed QoT estimation method is enhanced by interfacing it with a physical layer database (PL-DB) that stores past measurements. The PL-DB can be updated periodically and/or whenever a new lightpath is established. The PL-DB stores the time of each measurement, and can remove measurements as time passes to account for ageing and other time varying effects. The accuracy of the estimation framework was shown in [9] to depend on the number of lightpaths of the $\mathbf{y}_M$ matrix (which ultimately affects the knowledge of the IA-link parameters). A criterion for adequate estimation accuracy is for the $\mathbf{y}_M$ matrix to be full rank, which means that there is enough information for all the IA-links.

Active monitoring lightpaths acting as probes can be used to enrich the $\mathbf{y}_M$ matrix, when the established lightpaths are not enough to yield the required estimation accuracy. These active monitoring lightpaths can use any spare transceivers (e.g. employed for protection/restoration) or cheap transceivers designed for monitoring purposes, which do not need to be fully functional. In this paper we describe an algorithm to establish the appropriate monitoring lightpaths in order to improve the accuracy of the QoT estimation.

3. ACTIVE MONITORING LIGHTPATHS

3.1 Problem Statement

Given a set of available monitors M at a set of nodes U and the network state, that is the set C of established lightpaths (or an empty network), we want to define rules in order to decide which active monitoring lightpaths to establish and delete, including time, path and wavelength (or spectrum slots) and transmission parameters (if configurable) to use, so that we obtain more accurate QoT estimations. In essence, we want to fill the PL-DB with monitoring information for all the IA-links. Note that the deletion of lightpaths can provide the needed information for some IA-links, because it modifies the neighbours of the lightpaths co-propagating with the ones that were deleted. The goal of the algorithm is to extend the IA-graph routing matrix R and add the appropriate amount of entries so that it becomes full rank. We also want to minimize the duration of the whole process since the time for establishing, measuring, and tearing down a lightpath is not negligible, energy is consumed, and the operating lightpaths of the network are affected (due to interference) by this process.

3.2 Algorithm for active monitoring lightpath establishment

We will now describe the proposed heuristic algorithm assuming that we start from an intermediate monitoring network state (called current state) and we want to decide on the new state to move. In the current state we have established a set of monitoring lightpaths N. At any given time each monitoring transponder of the set M must be used once. The algorithm assumes that we pre-calculate k-paths for each pair of nodes in U. To obtain the next network state, the algorithm decides on which monitoring lightpaths to establish and which to delete. These are searched according to the following greedy manner:

1) We examine all the set of paths from the set of candidate paths. If all transponders are used we go to step 5.
2) For each path, we examine each available wavelength (or spectrum in certain granularity) up to the maximum wavelength (or spectrum) that is currently used in the network, taking into account the distinct wavelength (or spectrum) assignment. We route the lightpaths one at a time in the IA-graph G'. Note that adding the new monitoring lightpath results in re-routing of some lightpaths (monitoring or operating) in G'. This results in the updated routing matrix R with a possible higher rank.
3) If at least one of the candidate new monitoring lightpaths increases the rank, we select the one that increases the rank the most, and establish that. The algorithm starts over at step 1 if the routing matrix is not full rank.
4) If the rank is not increased by adding a single new monitoring lightpath, we examine cases where we establish concurrently two, three,…, or up to $|M|/2$ new monitoring lightpaths. Initially, we establish one new monitoring lightpath (the shortest path that crosses one link for which we have an unknown IA-link) and go back to steps 1-3. Given the new monitoring lightpath, we examine each candidate second lightpath through steps 1-3 and select the one that increases the rank the most. If the rank is not increased, then we repeat the same step until we have used all the available monitoring transponders.
5) We reach this step when all the monitoring transponders have been used. In this case we start deleting monitoring lightpaths in order to establish new ones in the following way.
6) We examine the deletion of one lightpath at a time. Each deletion can result in reroutings of the remaining monitoring lightpaths and the operating lightpaths C in the IA-graph. We delete the one that increases the rank the most.
7) If deleting one monitoring lightpath does not increase the rank, we examine the combinations of one deletion and the addition of a new lightpath. We select the deletion/addition combination that increases the rank the most.
8) If step 7 does not result in a rank increase, then we delete one lightpath at a time depending on which crosses the most links for which we have the most IA-link information and then we go back to step 7. When all the active monitoring lightpaths have been removed, we go to step 1.

4. RESULTS

To evaluate the performance of the heuristic algorithm we performed extensive simulation experiments. We compare the proposed algorithm to a naïve algorithm that focuses on one link at a time and establishes lightpaths in order to obtain information for all the related IA-links. Our main performance metric is the number of network monitoring states that is required to obtain a full rank routing matrix for the IA-graph, which is considered to yield accurate QoT estimation using the QoT tool of [9]. We also measure the number of lightpaths that are established, which is considered a less important metric. We assume the DT topology with 3 different load scenarios: an empty network, 44 and 85 already established bidirectional lightpaths. The results are averaged over 100 instances, for the cases of 44 and 85 bidirectional established lightpaths.

Figure 1a presents the number of network states required to reach a full rank routing matrix for the three traffic load scenarios examined. We observe that the number of network states required decreases as the number of already established lightpaths increases. This is expected since the larger the number of already established lightpaths, the more information is already present in PL-DB (i.e., the more populated the routing matrix is), and so fewer network states are required to fill it. The proposed heuristic algorithm requires fewer number of networks states when compared to the naïve approach. For an empty network the proposed algorithm requires ~60% fewer monitoring states when compared to the naïve algorithm, while when 85 bi-directional lightpaths are present in the network, it requires ~25% fewer states. As the load increases, the benefits of using the proposed algorithm, as opposed to the naive algorithm, decreases. This is due to the fact that as lightpaths are established for normal operation the PL-DB fills quickly, since a single lightpath may result in many IA-link entries (may use many links and it also interferes with the other lightpaths so it generates additional IA-link information). A few operating lightpaths are enough to collect information for the "easy" IA-links (zero or a few neighbours), which reduces substantially the number of states required for the naïve algorithm.

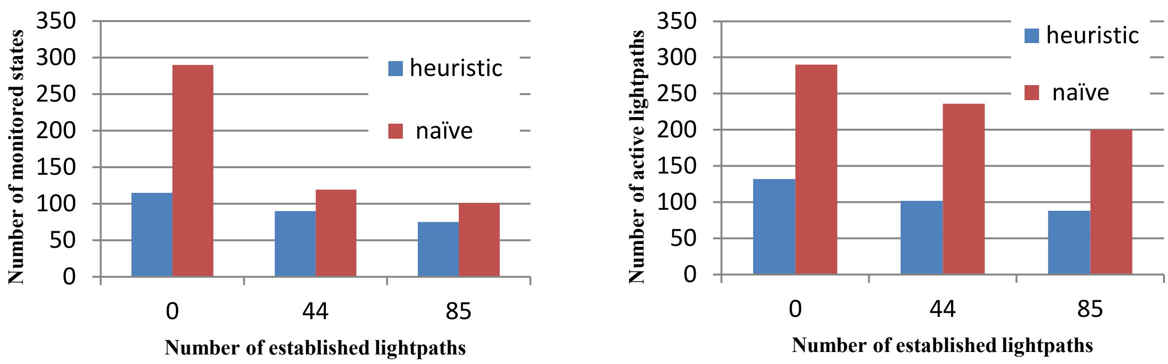

Fig. 1. Required number of a) states and b)lightpaths to fill the PL-DB and obtain accurate QoT estimations.

Similarly, the proposed heuristic algorithm requires fewer monitoring lightpaths to be established (Figure 1b), when compared to the naïve algorithm. In this case however, our proposed algorithm requires ~54% less lightpaths regardless of the initial number of established lightpaths. This can be attributed to the fact that the lightly loaded network already holds information about the "easy" IA-links with zero or few neighbors. Since the IA-links for which we need to acquire information represent states with many neighbors, a high number of monitoring lightpaths have to be lighted in order to obtain information about them.

5. CONCLUSIONS

We leveraged a QoT estimation tool that uses monitoring feedback to provide accurate QoT estimations and presented a scheme to establish active monitoring lightpaths in order to improve the QoT estimation accuracy. In order to obtain the required information our proposed algorithm requires up to 60% less monitoring states when compared to a naïve algorithm. The improved QoT accuracy can realize dynamic network re-optimization based on the actual conditions of the network and can also be used to reduce the provisioned margins which can result in significant equipment savings. Future plans include an algorithm based on Integer Linear Programming (ILP) to provide the optimal solution to the problem.

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