Cross-layer and Dynamic Network Orchestration based on Optical Performance Monitoring

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***Abstract*— An optical network, like any system, has to be observable before it can become subject to optimization. This is the main capability that the ORCHESTRA project introduces. ORCHESTRA's high observability relies on information provided by the coherent transceivers that can be extended, almost for free, to operate as software defined optical performance monitors (soft-OPM). Monitoring information is processed with correlation/data analytics algorithms to obtain an accurate knowledge of the physical layer. Cross-layer optimization algorithms use this knowledge to reduce the margins and operate the network close to its capabilities, yielding savings in equipment provisioning. Moreover, the network can be re-optimised according to actual traffic and physical layer conditions. Hard failures, such as link outages, can be restored faster while soft failures, such as equipment ageing or malfunctioning or interference due to higher load, can be identified and solved appropriately. ORCHESTRA's vision is to close the control loop, enabling maximal capacity efficiency and true network dynamicity.**

I. Introduction

The continuous growth of IP traffic and the emergence of new services are leading to a huge increase of traffic volume, with high unpredictability and dynamicity [1]. Future 5G networks will support a wide range of new services with extreme requirements, such as ultrahigh-definition video streaming, augmented and virtual reality, cloud gaming, smart homes, etc. Optical networking is a key to enabling the evolution towards 5G [2].

These motivates the design of a new truly flexible and programmable network. Typically, metro/regional and core networks rely on optical Wavelength Division Multiplexing (WDM) transport technology and are designed and operated in a static manner. All-optical connections (lightpaths) are overprovisioned for both physical layer attributes and capacity, and remain unchanged for several years. The current practice in the physical layer is to provide lightpaths with high *margins* to achieve uninterrupted network operation until its End-of-Life (EOL) [3][4].

When planning or upgrading the network, the Quality of Transmission (QoT) of the lightpaths is estimated using a "Q-tool" based on some physical layer model. In this QoT estimation, s*ystem margins* are used to anticipate future degradation due to equipment ageing, interference from increased load, and failures until the EOL [3][4]. For example, a typical assumption used is that of worst case interference, where interference is estimated as if the network operates at full load [5]. Moreover, to account for inaccuracies in the QoT estimation model itself, another margin, referred to as the *design margin*, is used on top of the EOL system margins [3][4]. The high margins result in deploying more equipment than is strictly necessary at the initial set-up time. Clearly, lowering the physical layer margins can yield significant cost savings [7][8][9][10].

The reduction of the system margins minimizes the equipment put in place, which then operates close to its limits. This increased efficiency yields significant cost savings but requires a dynamic network to address QoT degradations. Current optical systems cater for hard failures, through protection/ restoration mechanisms. As the system operates closer to its limits, *soft-failures*, QoT problems, could arise. The control plane needs to be able to process these failures in a dynamic manner and re-optimize the network accordingly. A dynamic control plane can also improve the restoration time of hard failures and increase network availability.

Elastic optical networks (EON) [11] provide finer granularity and flexibility as a means to improve network efficiency, reduce overprovisioning, and enable dynamic network re-optimization. However, before the network can be subject to optimization, its state has to be known, including physical layer performance. Current control and monitoring infrastructures do not adequately support this; coherent receivers can report a huge amount of data related to the physical layer, but this data is currently not exploited.

The vision of the E.C. funded project ORCHESTRA (www.orchestraproject.eu/) is to close the observe-decide-act loop, enabling network dynamicity and unprecedented efficiency [12]. ORCHESTRA relies on information provided by the coherent transceivers that are extended, almost for free, to operate as software defined optical performance monitors (soft-OPMs). Novel digital signal processing (DSP) OPM algorithms are developed to improve the monitoring capabilities of the coherent transceivers [13]. ORCHESTRA leverages on a novel hierarchical monitoring infrastructure to efficiently transfer and manipulate monitoring information from multiple soft-OPMs [14]. This enables a more accurate knowledge of the physical layer and QoT estimation with high accuracy [15][16], which in turn permits a fine, cross-layer optimization [5]. The Just in Time (JIT) nature of this continuous re-optimization, reduces overprovisioning and transmission margins and obtains savings in equipment and investments [9][10]. Moreover, higher physical layer observability can be used to efficient localize and handle hard and soft failures [17][18][19][20][21] and thus increase network availability. Figure 1 outlines the observe-decide-act control loop concept envisioned by ORCHESTRA.

The paper is organized as follows. In Section II we provide an overview of ORCHESTRA. In Sections III to V we provide examples of how network feedback can be exploited, In particular we present a correlation algorithm to estimate lightpaths' QoT, a dynamic network optimization algorithm and an algorithm to provision lightpaths with reduced margins. Finally, Section VI describes our conclusions.

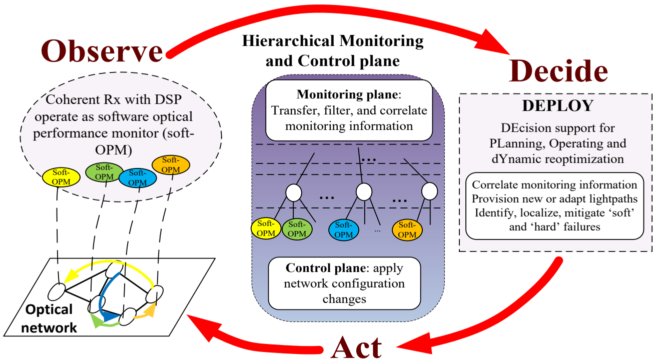

Figure 1: The ORCHESTRA observe-decide-act control cycle.

II. THE ORCHESTRA SOLUTION

The future of optical networks is coherent and elastic: telecom operators are deploying today a coherent, multi-format optical transport layer [11]. The multi-format transceivers are combined with flex-grid switches to enable higher rates. The coherent transceivers leverage DSP in powerful ASICs to enable more robust transmissions. This allows to shed redundant hardware (e.g. dispersion compensation modules), simplifying network design. ORCHESTRA [12] exploits these evolving trends and pursues the development of advanced DSP algorithms that adds real-time impairment monitoring capability to optical transceivers.

Potentially, every coherent transceiver in the network can be used as a software defined optical performance monitor (soft-OPM). Moreover, the monitoring functions come almost for free: coherent receivers already use ASICs for DSP. In addition to algorithms for measuring and mitigating dispersion effects (present in current transceivers), ORCHESTRA works on algorithms to measure optical signal to noise ratio (OSNR), and filtering effects [13].

The ORCHESTRA network has a plethora of soft-OPMs to extract physical layer information. But we can do even more: a soft-OPM at a receiver provides aggregate measures over a path usually traversing several fiber spans and links. ORCHESTRA uses correlation/data analytics algorithms to combine and correlate information from multiple soft-OPMs throughout the network. This enables new/improved capabilities, such as: accurate quality of transmission (QoT) estimation before lightpath establishment taking into account current network conditions [15][16]; detection, as well as anticipation [17], localization [18][19] and recovery from 'hard' (total) and 'soft' (QoT degradation) failures [20][21]. Note that such correlation methods make the gradual deployment of ORCHESTRA more appealing, since added value comes even from just a few OPMs.

ORCHESTRA also develops a hierarchical control and monitoring infrastructure [14]. ORCHESTRA hierarchical monitoring plane enables the effective processing of monitored information (filtering, correlation) and fault management, avoiding bottlenecks caused by traditional centralized approaches. The control functions that are considered include the tuning of transmission parameters of flexible transceivers (changing modulation format, FEC, power, etc), shifting in spectrum domain (push-pull [22]) or rerouting over the spectrum or space. Depending on the problem at hand, its solution is initially examined at a local level for single connections. If it cannot be solved locally, the problem is handled progressively at higher hierarchy levels where multi–connection actions are considered. In this way the complexity and the interventions are kept low, and we avoid creating bottlenecks at the central controller.

The introduction of elastic networking increased vastly the optimization dimensions, while new types of problems emerged. ORCHESTRA relies on the feedback from the soft-OPMs to develop true cross-layer optimization algorithms, targeting both offline (planning) but also dynamic use cases. In particular, ORCHESTRA develops multi-period planning algorithms that take into account the actual physical network state to provision lightpaths with reduced margins [10]. Dynamic optimization algorithms are also developed to operate the network close to its capabilities [27], resolving soft and hard failures efficiently [20], and continuously re-optimize the network, over an infinite time horizon.

A set of use cases to showcase and validate the benefits of ORCHESTRA were identified:

1) Lightpaths provisioning with reduced margins: during the planning for an upgrade, decisions on equipment purchase and (re-) configuration of lightpaths are taken. These decisions are made by an optimization algorithm that uses QoT estimates (typically with high margins). ORCHESTRA proposes this planning process to be done with reduced margins, based on the actual network conditions as observed through the soft-OPMs.

2) Dynamic network adaptation: ORCHESTRA develops mechanisms to support dynamic network re-optimization based on the actual traffic and physical layer conditions as opposed to the overprovisioning of network resources.

3) Hard-/soft-failure localization and hard-failure prediction: It has been observed that a huge number of alarms are generated in Optical Transport Network (OTN) [14], while alarm suppression mechanism are quite slow. ORCHESTRA's hierarchical monitoring plane provides an efficient and scalable infrastructure that filters and correlates alarms in order to suppress their number and localize the failure. ORCHESTRA's advanced monitoring functions enables also the localization and handling of soft-failures (QoT problems) e.g. due to malfunctioning or ageing of equipment or increased interference in a network operated with low margins. Moreover, transmission parameters (e.g. State Of Polarization) can be measured through DSP, and be used to predict link outages/ hard failures [17].

4) Transmission optimization during network upgrade and maintenance tasks: Network upgrades and maintenance tasks are a gradual procedure; during upgrades the network remains in operation but is vastly un-optimized. With ORCHESTRA it is possible to optimize the network even during the upgrade/ maintenance processes.

5) Alien lightpaths support: Aliens are lightpaths for which the operator does not have knowledge on their transmission parameters. As such, they might cause soft-failures, e.g., have high launch power or be misaligned with filters, creating high crosstalk and nonlinear interference. It is also hard for aliens to obtain good QoT over an unknown domain. ORCHESTRA advanced monitoring functions can provide efficient solutions to aliens' QoT issues.

EON has increased vastly the number of dimensions (choices) available for optimization, motivating the definition of new optimization problems. Cross-layer optimization, enabled through monitoring, is key to unleashing the full potential of elastic optical transceivers (EOTs). In the following we focus on some of the cross-layer optimization algorithms that are developed in the framework of the ORCHESTRA project.

III. Correlation Algorithms for QoT Estimation

Estimating the QoT, performed by Q-tool, is fundamental when planning or upgrading the network. QoT estimation methods range from very complex ones to simulations and analytical models of lower complexity (e.g. GN model [22]). Such models require accurate knowledge of the physical layer parameters. Since it is not possible to have such accurate knowledge, design margins are used to account for the inaccuracies, while system margins are used to account for equipment ageing, increased interference as load increases with time and anticipate future failures.

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 [15] [24] or feed the Q-tool with better parameters, thus reducing the design margin. The method developed in [15] takes into account the dependencies among the different routes and the relative spectrum positions of the lightpaths, and correlates information network wide to accurately estimate the QoT of new lightpaths with actual system and reduced design margins. Also, the work presented in [19] can improve the accuracy of monitored information of existing paths. In this way the accuracy of the QoT estimation can be further improved.

In particular, in [15] we consider that the monitoring plane is responsible to collect and keep a database with the SNR values of the established lightpaths. The network is represented by graph G with a set M of established lightpaths, which define what we call the *state* of the network. 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 monitored 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 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

$$\mathbf{y} = \begin{bmatrix} \mathbf{y}_M \\ \mathbf{y}_N \end{bmatrix} = \begin{bmatrix} R_M \\ R_N \end{bmatrix} \mathbf{x}, \qquad (1)$$

The impairment values in vector $\mathbf{y}$ can be different for different use cases. Assuming that we want to estimate the QoT, we take $\mathbf{y}_M$ 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, for a given 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 [24].

The above definition of matrix R depends only on paths and is thus able to convey information only on routing (space) dependencies, while it ignores spectrum dependencies. To account for interference, and thus obtain higher QoT accuracy, we extend the above model. We define an interference aware (IA-) transformed graph G', where each link in G is replaced by a set of IA-links in G' that represent the position of the active lightpaths on each link. The underlying assumption is that lightpaths with same relative position of active neighbors 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 matrix R_M. Using this routing matrix in the above problem formulation we obtain QoT estimates that account for actual interference. The cost we pay for the improved estimates is a (manageable) increase in processing complexity (e.g., the size of vectors $\mathbf{y}$ and $\mathbf{x}$ and matrices R_M and R_N in Eq. (1) increase)

The above formulation is extended to work with lightpaths that utilize various modulation formats, baud-rates, and spectrum. To reduce the problem space (expanded graph) we need to group some transmission options. As expected the accuracy of the QoT estimation reduces the more the transmission options are, or, stated differently, more established lightpaths are required to get the same accuracy.

The proposed QoT estimation method is enhanced by interfacing 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 details of the interface of the PL-DB with the QoT estimation module is carried out in the framework of the ORCHESTRA project.

To evaluate the performance of the QoT estimation scheme we carried out extensive simulations [15]. In the following we present results for NSFNet topology, assuming WDM and 2 transmission scenarios: "WDM- 1 baud-rate" scenario assumes 100Gbps PM-QPSK with 28 Gbaud, while the "WDM- 2 baud-rates" scenario assumes two different baud-rates existing at the same time in the network: 28 and 32Gbaud, which are represented by different IA-links in the graph transformation. Links were assumed to consist of single mode fiber (SMF) 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, the noise figure of EDFAs was set to 6 dB. We assumed the GN model [22] as the ground truth for the physical layer; it was used to generate the monitored values and also to check the accuracy of the estimation. Lightpath requests arrive according to a Poisson process, have exponentially distributed duration and uniformly distributed destinations. A request is served using a shortest path routing/ first-fit wavelength assignment algorithm.

Figure 2 shows the Mean Squared Error (MSE) for the pre-FEC BER estimation as a function of the number of IA-lightpaths available in the database (PL-DB). Note that the PL-DB is filled up quickly, since establishing a new lightpath creates interference and thus reroutes several IA-lightpaths, which in turn generates new entries in the PL-DB. As expected, when the number of IA-lightpaths in database is low, the MSE is high, due to inadequate information. The accuracy is worse in single link lightpaths. Single link lightpaths have robust BER much above the limit, making such inaccuracy insignificant in practice. To show this, in Figure 2 we also plot the MSE for lightpaths consisting of at least two links, which is observed to be much lower. To achieve a negligible MSE in the WDM NSFNET network the database must have around 400 IA lightpaths (about 160 established lightpaths) for the single baud-rate, and around 700 (about 180 established lightpaths) for the dual baud-rate transmission scenarios.

Another interesting metric is the maximum underestimation (MU), since this gives the design margin needed to work on the safe side (never underestimate the QoT). For the single baud-rate scenario the MU was 0.1 dB (pre-FEC BER) for 1000 IA-lightpaths, while for the two baud-rates scenario, the same MU required around 1800 IA-lightpaths. Note that MU, as was also the case for MSE, falls as more lightpaths are established. So the design margin falls as time advances, more lightpaths are established, and we obtain a better understanding of the physical layer.

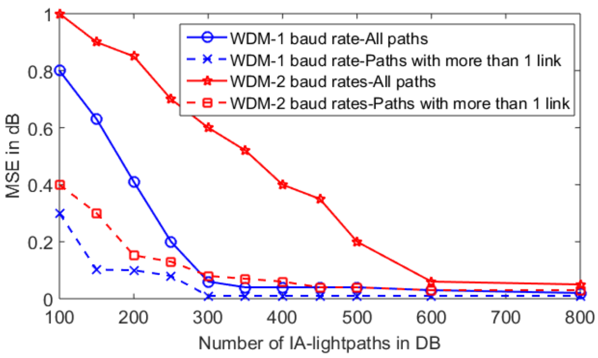

Figure 2: The Mean Squared Error (MSE) of pre-FEC BER estimation for two WDM scenarios as a function of the entries in the database.

Similar results were obtained for an EON, with more transmission options. As expected the estimation accuracy worsens as the number of transmission options increases, but still the accuracy is quite good and the related margin quite low. Additional methods that exploit temporal correlation to reduce uncertainty are under development [19]. In the last section of this paper we show how the high accuracy/ low margins can be translated into cost savings.

IV. Dynamic Cross-Layer Optimization

ORCHESTRA develops algorithms to dynamically adapt the network in accordance with the use cases presented in Section II. To be more specific, we develop algorithms to re-optimize the network, according to traffic variations, or recover from soft failures, keep high efficiency during maintenance tasks, and handle alien lightpaths. The reconfiguration actions need to take into account the physical layer conditions. In the following we discuss an algorithm that recovers from a soft failure [20], but similar approaches are considered in the other use cases.

If a lightpath suffering from a soft failure (i.e., its QoT falls) moves close to its FEC threshold, we want to avoid rerouting it or adding new regenerators. So our goal is to find the set of re-configuration control actions (for the lightpath at hand but also for other lightpaths in the network) that solve the QoT problem at hand but also have low control plane overhead. To increase the QoT of the lightpath, we harvest the flexibility degrees of elastic transceivers and switches. The toolkit we developed considers the following actions.

- FEC adaptation: we assume FEC tunable transceivers and lightpaths provisioned with reduced margins. In such an environment there are cases where the most robust FEC available was not used: the selected lower FEC yields acceptable QoT and requires fewer slots (e.g. for 25 net baud-rate, using 12% or 28% FEC results in 3 or 4 slots, respectively).
- Creating spectrum guard-band: Reducing interference increases the QoT and can be achieved by using spectrum as guard-band, i.e., leaving spectrum space between lightpaths.
- Modulation format adaptation: Adapting transmission to a more robust modulation format can improve substantially the QoT of the lightpath.

Assuming that we want to keep the same net rate, in the first and third options we need to increase the baud-rate accordingly. So, all the aforementioned options require some extra spectrum for the problematic lightpath. For the first and third options this is due to the increase of the baud-rate, while the second option relies exactly on the creation of spectrum guardband. The push-pull technique [22] can be used to perform the required spectrum reconfigurations in a hitless (without traffic interruption) manner.

In addition to failure resolution, our secondary goal is to avoid a high number of control operations. Since all the aforementioned options can provide a solution to the QoT problem, our algorithm investigates them in the order presented above, considering cheaper, from the control plane point of view, the adaptation of the FEC, and most expensive the adaptation of the modulation format (which probably results in loss of data).

Taking all above into account, the algorithm decides on the reconfiguration actions to perform, by examining the actions in the above order. Since each action requires some spectrum space, it examines how to create the required space, by recursively pushing the adjacent lightpaths. In doing so, it tries all the possible combinations of slots both higher and lower to the occupied spectrum, and chooses the one resulting in the lowest number of pushed lightpaths. The algorithm also needs a fast and accurate QoT estimation, to verify when the problem is fixed. For this, we use the correlation method presented in Section III.

To evaluate the efficiency of the proposed algorithmic toolkit we performed extensive simulation experiments. We assumed a network inspired by the Telecom Italia European backbone Span characteristic were the same as in the previous Section. We examined two traffic loads: 20 and 50 Tbps. We assumed 100 and 200 Gbps connections that are served using the following options: modulation format: PM-16QAM, and PM-QPSK, baud-rate: 28, 32, 56, 64 Gbaud, and FEC: 12% and 28%, with pre-FEC BER threshold of -2.2dB and -1.88dB, respectively.

In the simulations we considered that a single link at a time suffers a soft failure (e.g. due to equipment malfunctioning) which results in an SNR degradation of 1, 2 or 3 dB. For each single link soft failure we examine if the proposed toolkit can absorb the created QoT problems by re-configuring the lightpaths that fall below the QoT threshold, and otherwise we place regenerators. Regenerators placed can be re-used when examining a different link failure (following the concept of backup multiplexing restoration [26]). We compare: (i) The proposed re-configuration toolkit, (ii) Soft-failure protection: here, we use margins and decide on transmission configurations and place regenerators; the margins are used to absorb the QoT problems. This is equivalent to soft-failure protection, as one single-link failure is examined at a time and we decide the transmission configuration of the lightpaths and place regenerators to protect against that. The decisions are kept when we examine the next link failure.

Figure 3 presents the required number of regenerators. In case (i), which relies on backup multiplexing, we calculate the required regenerators per node, and then sum the final numbers for each node. In case (ii) we sum the regenerators for each node. Our toolkit requires approximately at least 22% less and at most 40% regenerators than case (ii), depending on the severity of the soft failure. The spectrum utilization is 2% lower, since we examine restoration for each single link instead of all link failures.

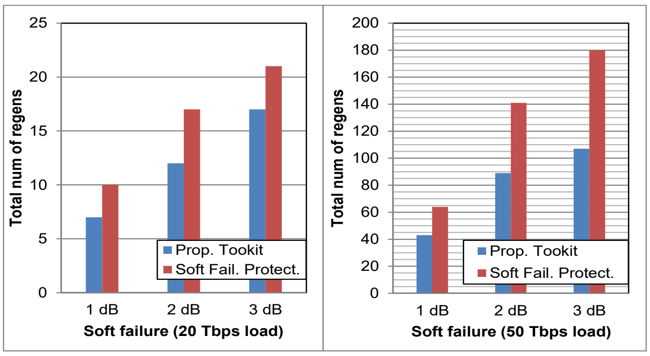

Figure 3: The total number of regenerators to recover from a single link soft failure of 1, 2 and 3 dB for 20Tbps and 50Tbps loads.

V. Cross-Layer Planning with Reduced Margins

Traditionally, lightpaths are provisioned with high margins (EOL system margins plus a design margin), which reduce optical reach and require deploying more regenerators and more robust transponders than necessary. ORCHESTRA provides mechanisms to reduce these margins with just in time (JIT) deployment of equipment based on network feedback. Real (as opposed to worst case) QoT estimates (Section III) are used when provisioning, and dynamic actions (Section IV) are used to resolve any issues that arise from the reduced margins and operation close to the limits.

To harvest this, ORCHESTRA has developed a heuristic algorithm to provision lightpaths with reduced margins [10]. We consider a network with tunable transponders whose feasible configurations are given by a set of transmission tuples. We study a multi-period planning problem where tunable transponders can be re-configured at intermediate periods or regenerators can be added to absorb traffic increases or cope with QoT deterioration due to equipment ageing, failures or increased interference.

The developed algorithm consists of a pre-processing phase, which calculates the set $Q_{s,d}$ of candidate (path p, transmission tuple t, regeneration points r) triples that can be used to serve a demand from s to d. Since the transmission reach depends on the current network state (including ageing and interference), in the pre-processing phase we create a set of triples for the possible set of nodes where regenerators may be placed, taking into account only the ageing effects. Then, the algorithm serves the demands one-by-one in a particular order. For each demand, it considers the pre-calculated (p,t,r) triples, and for a given triple, considering the related regeneration points, the algorithm allocates spectrum to the sub-paths (transparent lightpaths). Then it uses the Q-Tool (e.g. the correlation algorithm reported in Section III or the GN model) with input the current utilization of the links to account for actual interference, in order to determine (i) if this sub-path has unacceptable QoT or (ii) if it turns infeasible some previously established lightpath. If the answer to any of the two questions is yes, the algorithm searches for a different spectrum allocation, examining also cases with spectrum guardband between the lightpaths, to reduce interference. We repeat the above process for all sub-paths, and when it is successful, the algorithm considers the triple as feasible. If not successful, it continues with the next triple. After examining all the triples, we select the one whose spectrum allocation minimizes the objective:

$$\underset{(p,t,r)\in Q_{s,d}}{\mathrm{Min}} \left(w\cdot S_{p,r,t}(\tau) + (1\text{-}w)\cdot C_{p,r,t}(\tau) \right)$$

where $C_{p,t,r}(\tau_i)$ is the cost of triple (p,t,r) calculated by adding the prices of equipment and $S_{p,t,r}(\tau_i)$ is the total spectrum required by this triple, and w is a weight used to assign the desired relative importance to the two optimization parameters. In the multi-period scenario, the above objective is evaluated in each period, subtracting the cost of the previous periods. So the objective becomes then the minimization of the added cost in each period.

To quantify the savings that can be obtained by reducing the margins we performed detailed studies in metro-regional, national [9] and continental size networks [10]. In the following we briefly describe the findings of the continental size network in which we used the above algorithm.

In particular, we study the multi-period planning in a network inspired by the Telecom Italia European backbone. We modeled the ageing effect of the following equipment: fiber (increase of attenuation coefficient and splice to repair cuts), transponders (lower sensitivity) and amplifiers (increase of noise figure). Table 1 presents the related contributions to the begin-of-life (BOL) and end-of-life (EOL) margins and we assumed a linear (in dB) projection for intermediate years. We also assumed the use of a 2dB design margin at BOL that can be reduced to 1dB by learning/understanding the network (Section III).

Table 1: Begin-of-Life (BOL) and End-of-Life (EOL) margins for a 10 year network lifetime.

Margins	BOL	EOL
System margin: Fiber attenuation coefficient (dB/km)	0.22	0.25
System margin: Noise Figure EDFA (dB)	4.5	5.5
System margin: Transponders sensitivity margin (dB)	1	1.5
Design margin (dB)	2	1

We examined the planning over 10 periods (~10 years) with realistic traffic consisting of a mix of 100, 200, 400 Gbps clients (400 Gbps appear in period 4), increasing by 25% every 2 periods. Initial traffic was 20 Tbps and increased to 186.3 Tbps at period 10. We assumed two types of tunable transponders (BVTs): (i) supporting 100 and 200 Gbps by tuning up to DP-16QAM and 43 Gbaud, and (ii) supporting 100, 200 and 400 Gbps by tuning up to DP-64QAM and 64 Gbaud. The second transponder was available at period 4. A single transponder was used to match each client, without grooming or muxponders. Due to long continental links, we allowed the use of regenerators with the same specifications and prices equal to 0.8 of those of transponders. We also assumed price decline of 10 % per period.

We compare: (i) planning with *actual margins*, where at each period both system and design margins fall according to the BOL-EOL values of Table1, (ii) planning with *actual system margins* (that is with BOL design), and (iii) planning with *worst case margins*, where we use EOL system and BOL design margins. When planning with *worst case margins*, transponders are reconfigured and transponders and regenerators are added to account only for traffic increases, since EOL system margins already account for ageing deteriorations. In the other two cases, where reduced margins were used, in addition to traffic increase, the same actions are taken to resolve QoT deteriorations due to ageing and increased interference. The reduction of the design margin somehow balances the ageing and interference effects.

Figure 4a presents the total number of transponders and regenerators employed in the examined periods. We notice that in the early periods, planning with *actual margins* and *actual system margins* results in substantially lower number of regenerators. This is due to the reduction of the system margins, which postpones the purchase of the related equipment. Apart from postponing, the reduction of the design margin (only in *actual margins* case) results in avoiding the purchase of equipment, as clearly seen at the last period when comparing planning with *actual margins* with the *worst case margins*. Planning with *actual system margins* results at the end in the same number of equipment with the *worst case margins*. Both, postponing and avoiding the purchase of transponders and regenerators, results in cost savings, which are shown in Figure 4b. The savings obtained are higher during the early periods, and at the end were about 12% for *actual margins* and 24% for *actual system margins*, for 10% price depreciation per period.

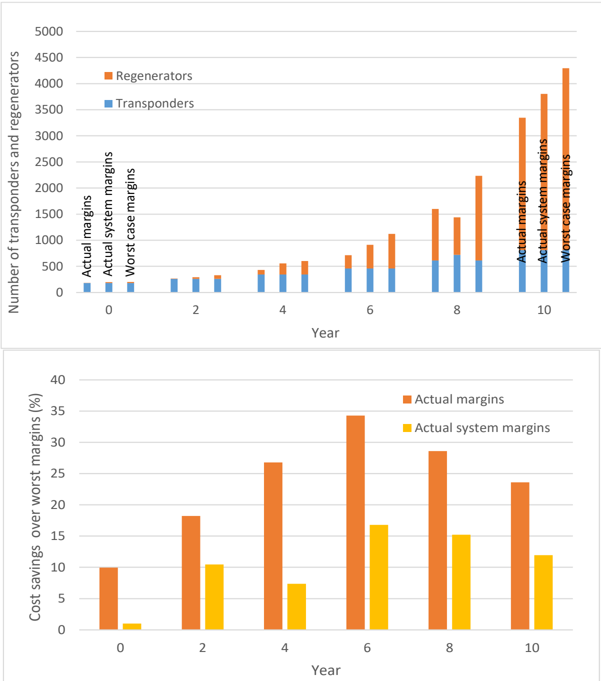

Figure 4: (a) Total number of deployed elastic transponders and regenerators for actual margins, actual system margins, and worst case margins. (b) Cost savings when planning with actual margins, and actual system margins over worst case margins, assuming 10% depreciation per period.

A fact that was not included in the above calculations is that the network operator can invest the savings of intermediate periods with interest, yielding extra savings for the ORCHESTRA solution, e.g. for the proposed solution (*actual margins*), 10% price depreciation and 2% interest per year, we end up with 28% savings.

VI. CONCLUSIONS

ORCHESTRA relies on information provided by coherent transceivers that can be extended, almost for free, to operate as software defined optical performance monitors (soft-OPMs). Novel DSP algorithms for real-time multi-impairment monitoring are developed and combined with a novel hierarchical monitoring plane to handle monitoring information in an efficient and scalable manner. Impairment information from multiple soft-OPMs is correlated, to provide an even better understanding of the physical layer. The advanced monitoring functions used in optimization procedures enables true cross-layer optimization, yielding higher network availability and unprecedented network capacity efficiency, as indicated by realistic case studies for metro, national and continental size networks

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