

Lightpath Establishment Assisted by Off-line QoT Estimation in Transparent Optical Networks

Nicola Sambo, Yvan Pointurier, *Member, IEEE*,

Filippo Cugini *Member, IEEE*, Luca Valcarengi, *Member, IEEE*, Piero Castoldi, *Member, IEEE*, Ioannis Tomkos, *Member, IEEE*

Abstract—We propose lightpath establishment techniques for transparent optical networks, valid for both a *centralized path computation* (i.e., performed by *path computation element - PCE*) and *distributed path computation* (i.e., performed by each ingress node). The proposed techniques rely on correlating the end-to-end Quality of Transmissions (QoT) (e.g., optical to signal noise ratio - OSNR) of lightpaths already set up to evaluate the QoT of lightpaths to be established. The correlation is leveraged by two end-to-end estimation frameworks called “network kriging” and “norm ℓ_2 minimization”. Each framework is used in turn to estimate end-to-end parameters that describe the QoT for a lightpath to be established, based on measured parameters from other lightpaths that were previously established or probed. Simulations are carried out for both PCE and distributed networking scenarios on a sample optical transparent network. The proposed lightpath establishment techniques reduce the probability that a set up attempt is unsuccessful due to unacceptable QoT, and reduce the number of set up attempts to successfully establish lightpaths. Simulation results are also provided to show that our techniques permit a fast convergence of QoT information at PCE or ingress nodes in the context of dynamic networks.

Index Terms—QoT, transparent optical networks, PCE, GMPLS, network tomography.

I. INTRODUCTION

DYNAMIC transparent optical networks, where lightpaths are provisioned and established on-demand, are widely seen as the key enabling technology for the core network of the future [3]. Indeed, in such networks, the removal of Optical/Electrical/Optical (OEO) conversion can decrease both CAPEX and energy consumption at the same time [4], while the increased available bandwidth and flexibility can decrease OPEX.

A drawback of transparency is the increase of physical propagation distances over which physical

layer impairments accumulate, potentially resulting in unacceptable lightpath Quality of Transmission (QoT) [5], typically measured in terms of Bit-Error Rate (BER). In GMPLS-controlled transparent optical networks, path computation may be either distributed, i.e. performed at each ingress node, or centralized, e.g. performed by a Path Computation Element (PCE) [6]. A PCE is an entity capable of computing paths requested from Path Computation Clients (PCCs) based on a network graph, applying, if needed, computational constraints for instance on bandwidth and QoT.

Since QoT must be satisfied along a path, several techniques have been proposed to evaluate it. QoT can be evaluated through *estimation* or measurements (*monitoring*). Analytical models can estimate QoT, before a lightpath is established, based on the prior knowledge of network physical parameters (evaluated at network installation time or through live monitoring) [5], [7]–[12]. In case of QoT estimation, mechanisms are required to provide either the centralized PCE or the ingress nodes with updated QoT information. Extensions to the PCE architecture [13] or to the GMPLS protocol suite (e.g., to the routing protocol [14], or the signaling protocol [15]) have been proposed to encompass QoT information. In the case of centralized PCE architecture, thanks to the centralized nature of the path computation, effective Traffic Engineering (TE) solutions are potentially achievable. However, additional mechanisms to provide the PCE with QoT information are required, e.g. a dedicated communication between monitors and the PCE, as discussed in [13]. In the case of GMPLS routing protocol extensions, QoT parameters are flooded within the entire transparent optical network through OSPF-TE protocol. On the one hand, this enables each source (i.e., ingress) node to estimate lightpath QoT along any possible route toward each destination. On the other hand, this may affect control plane scalability and convergence performance. In the case of GMPLS signalling protocol extensions, QoT information is included within RSVP-TE signalling messages. Thus, each node becomes aware of only the QoT information associated to lightpaths for which the node is either a transit or an end point. On the one hand, with respect

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N. Sambo, L. Valcarengi and P. Castoldi are with Scuola Superiore Sant’Anna, Pisa, Italy. At the time this work was performed, Y. Pointurier was with Athens Information Technology, Athens, Greece. I. Tomkos is with Athens Information Technology, Athens, Greece. F. Cugini is with CNIT, Pisa, Italy.

to routing protocol extensions, this improves control plane performance scalability. On the other hand, signaling protocol extensions may prevent lightpath QoT estimation before lightpath set up due to lack of QoT information at a source node. In this case, a lightpath set up attempt is required for retrieving lightpath QoT information and perform QoT estimation. If the estimated QoT is unacceptable, the lightpath set up is blocked and another attempt might take place, delaying the lightpath set up. IETF is more inclined to encompass QoT information within the PCE Architecture or the GMPLS signalling protocol and not within the routing protocol because of scalability reasons [16]. For this motivation, in this paper we concentrate on both the PCE-based and the signalling-based solutions.

When the QoT is evaluated through measurements, monitoring techniques can be used during the lightpath establishment to assess more directly whether the signal's QoT is acceptable [17]–[19]. Measurements on probe traffic aims at removing any inaccuracy stemming from analytical models. For this reason, probing is also considered in the paper. In particular in [18], a lightpath establishment scheme is assisted by monitoring and probing, in which probe traffic is sent and BER is measured just before lightpath activation (i.e., before client data transmission). However, with probing, the lightpath establishment could be delayed. Indeed, if the measured QoT is unacceptable, the lightpath establishment is blocked and another attempt might take place increasing the set up delay and wasting the resources reserved before probing. Therefore, lightpath establishment techniques are required that guarantee the QoT with limited knowledge of QoT information and reduce the number of establishment attempts.

In this paper, lightpath establishment techniques exploiting both QoT estimation and monitoring are proposed for distributed and centralized (i.e., PCE-based) path computations. Monitoring information is exploited by QoT estimation, which allows to speed up the lightpath establishment by avoiding establishment attempts along paths that are infeasible in terms of QoT. Hence, we propose to infer or estimate QoT parameters for lightpaths, given the knowledge of monitoring data previously collected for other lightpaths. Here, we propose to apply two estimation techniques, called “*network kriging*” [20] and “*norm ℓ_2 minimization*” (i.e., ℓ_2 -min) [21], typically used in “*network tomography*” [22], in the context of dynamic transparent optical networks. The two estimation frameworks leverage the correlation between QoT parameters related to lightpaths with common links. The PCE, in the PCE-based scenario, or the ingress node, in the distributed scenario, compute the paths to route the lightpath that has been requested. The PCE (or the ingress node) exploits available past probing data to estimate a new lightpath's QoT through network kriging or ℓ_2 -min. If the estimated QoT is acceptable, prob-

ing is performed to verify the lightpath QoT, otherwise, another path is computed. We show through simulations that the establishment techniques assisted by network kriging and ℓ_2 -min decrease the probability that a lightpath establishment attempt is unsuccessful, and thus reduces the number of successive attempts to successfully establish lightpaths in both network scenarios. We also assess with simulations that our techniques allow a fast convergence of estimated QoT parameters at each ingress (or PCE) node, an important property in the context of dynamic network scenarios where physical parameters may change with time and where management algorithms must adapt and react to changing conditions.

II. ESTIMATION FRAMEWORKS

In this section, we present the two estimation frameworks that we utilize to evaluate lightpaths' QoT based on the monitoring data collected during previous lightpath establishments. The two techniques are, namely, “*network kriging*” (further denoted by NK) [20], and a technique based on “*norm ℓ_2 minimization*” (further denoted by ℓ_2 -min) [21]. Both techniques rely on the correlation between end-to-end parameters that is induced by a network topology: the QoT parameters of lightpaths sharing a large number of links are highly correlated, while there is no correlation between the QoT of lightpaths that do not share any link.

In this study we consider four end-to-end parameters, which describe QoT, accounting for the following transmission impairments: amplified spontaneous emission (ASE), polarization mode dispersion (PMD), chromatic dispersion (CD), and self phase modulation (SPM). Note that all inter-channel other effects (such as cross-phase modulation – XPM, four wave mixing – FWM) are considered with fixed worst-case margins (i.e., all channels lit) as it is typically done by operators in current networks. Fixed worst-case margins are computed in the worst-case scenario during network installation considering the set of possible routes and all channels lit. Thus, fixed worst-case margins are applied during lightpath provisioning independently on the lightpath route. If a lightpath has acceptable QoT in the worst-case scenario, its QoT will be certainly acceptable also when new lightpaths are established. In this paper, a single bit-rate network (e.g., 10Gbit/s) is considered, however, in case of XPM in multi-bit rate networks, worst-case margins could be too pessimistic so that considering a guard band among interfering lightpaths can be a better solution than assuming worst-case margins [23].

The estimation frameworks assume the existence of a linear relationship between the link-level parameters and the end-to-end parameters to be estimated. In the considered optical networking context, linearity holds for each of the four aforementioned physical impairments; specifically:

- OSNR degradations are caused by the accumulation of the ASE noise; the inverse of OSNR is linear, i.e., by denoting with r_i the OSNR parameter of a lightpath using only the link i , the OSNR R_ℓ of a lightpath ℓ consisting of 2 consecutive links i and j is such that $1/R_{i,j} = 1/r_i + 1/r_j$;
- denoting by p_i the average PMD of link i (in ps), the PMD P_ℓ accumulated along a lightpath ℓ is such that $P_\ell^2 = p_i^2 + p_j^2$. Hence, the square of the average PMD accumulates linearly;
- CD accumulates linearly; denoting by d_i the dispersion parameter of link i (in ps/nm), $D_\ell = d_i + d_j$;
- SPM can be quantified through the nonlinear phase of the signal φ , which accumulates linearly [24]: $\Phi_\ell = \varphi_i + \varphi_j$.

Note that each of the four end-to-end parameters R , P , D and Φ can be monitored by using the appropriate hardware: OSNR monitor [17], [25], [26] for R , PMD [25], [27]–[29] and CD [30]–[32] monitors for P and D , respectively, and power monitor for Φ [24], making the QoT estimation via the estimation of OSNR, PMD, CD and nonlinear phase practical. Regarding nonlinear phase, Φ is computed by considering that fiber non-linear parameters (e.g., *effective area* – A_{eff}) are roughly constant and known for fibers from a given type [33], [34], and an over-estimate value can be used for each kind of fiber in the network. Then, the model in [15] is utilized to derive the lightpath QoT from R , P , D and Φ . D and Φ parameters are computed as penalty to the OSNR. Then, penalty and worst-case margins (to account for non-modeled effects as XPM) are subtracted from R to compute the final R_f . Finally, the lightpath QoT is estimated to be acceptable if: i) R_f is higher than a threshold which guarantees a maximum BER (e.g., 10^{-9} after forward error correction); ii) P parameter is below a threshold (e.g., 10 % of the bit duration).

A. Notation

Consider a network with E (unidirectional) links, and where L lightpaths are established. The network is abstracted through the routing matrix $G \in \{0, 1\}^{L \times E}$, where $G_{\ell,j} = 1$ when lightpath ℓ uses link j . Consider the end-to-end parameter values $\mathbf{y} \in \mathbb{R}^L$, where y_ℓ is a value for lightpath ℓ . We assume in addition that the end-to-end parameters \mathbf{y} can be written as linear combinations of link-level parameters $\mathbf{x} \in \mathbb{R}^E$. In particular, we assume that parameter y_ℓ is equal to the sum of the parameters x over all links used by lightpath ℓ , that is: $\mathbf{y} = G\mathbf{x}$. The end-to-end QoT parameters \mathbf{y} that we consider correspond to either $1/R$, P^2 , D or Φ , while the link-level QoT parameters \mathbf{x} correspond to either $1/r$, p^2 , d or φ .

We now assume that some of the end-to-end values in \mathbf{y} are already known through measurements, while others are not. We reorder the values within \mathbf{y} and the rows of G , as follows. Denote with \mathbf{y}_m the parameters

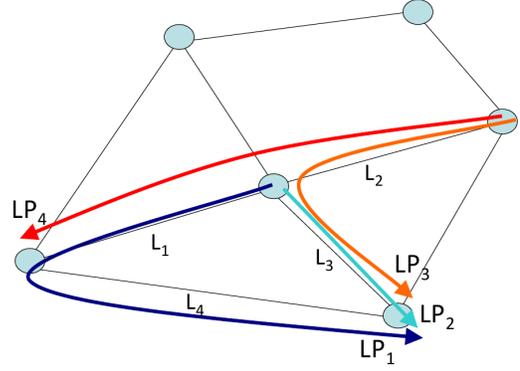


Figure 1. Illustrative example: estimation of the end-to-end properties of lightpath LP4 given the knowledge of the end-to-end properties of lightpaths LP1, LP2, LP3 obtained through monitoring.

of the lightpaths for which monitoring data are available and with \mathbf{y}_n the parameters for the lightpaths for which monitoring data is not available and that should be estimated: $\mathbf{y} = [\mathbf{y}_m^T, \mathbf{y}_n^T]^T$. Similarly, denote with G_m the matrix formed by the rows of G that correspond to lightpaths for which monitoring information is available and G_n the rows of G corresponding to lightpaths for which no monitoring information is available, such that: $G = [G_m^T, G_n^T]^T$. Then:

$$\mathbf{y} \triangleq \begin{bmatrix} \mathbf{y}_m \\ \mathbf{y}_n \end{bmatrix} = \begin{bmatrix} G_m \\ G_n \end{bmatrix} \mathbf{x}. \quad (1)$$

Consider for instance the network depicted in Fig. 1, where end-to-end parameters $\mathbf{y}_m = [y_1, y_2, y_3]^T$ for lightpaths LP1, LP2, LP3 are known (lightpaths may still be present in the network, or they may have already been torn down). If the demand for a fourth lightpath LP4 arrives, restricting our view of the network to the 3 links L1, L2 and L3 with respective link-level parameters $\mathbf{x} = [x_1, x_2, x_3]^T$, we have

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \quad (2)$$

Because all 4 lightpaths share the same set of links, it is possible to estimate $\mathbf{y}_n = y_4$ given y_1, y_2 and y_3 and the routing matrix G , using network kriging or ℓ_2 -min. We show how this is done in the following subsection.

B. Network kriging and norm ℓ_2 minimization

Consider the following general estimation problem: given a routing matrix $G = [G_m^T, G_n^T]^T$, the end-to-end observations $\mathbf{y}_m = G_m\mathbf{x}$ where the link-level parameters \mathbf{x} are unknown, determine all end-to-end parameters \mathbf{y}_n where $\mathbf{y}_n = G_n\mathbf{x}$. Network kriging and norm ℓ_2 minimization approximate \mathbf{y}_n as follows.

- **Network kriging (NK):**

using the notations above, the best (in terms of mean-square error) linear estimate $\hat{\mathbf{y}}_n$ for the

parameters corresponding to non-observed lightpaths can be shown, as in [20], to be:

$$\hat{y}_n = G_n G_m (G_n G_m^T)^+ y_m, \quad (3)$$

where $(\cdot)^+$ denotes a pseudo-inverse such as the Moore-Penrose inverse.

This estimator is presented in [20], together with an assessment of the scalability performance of the method: with NK, the computation time is dominated by matrix inversion operations and the complexity is $O(M^3)$, where M is the number of observed lightpaths. Thus, NK is particularly suitable in the case of a limited amount of observations, while it may suffer from scalability performance in the case of large amount of monitoring information.

- **Norm ℓ_2 minimization (ℓ_2 -min):**

it is also possible to seek nonlinear estimates of y_n although they can be more computationally intensive than linear estimates. In particular, one technique to estimate y_n consists in first finding an estimate of x verifying some property (such as x having a minimum for some norm). Several norms can be candidate to such minimization, but a particularly popular choice is the minimization of the ℓ_2 norm. In this case the aforementioned y_n estimation problem is equivalent to the problem of finding the solution x to the following minimization problem [21]:

$$\min_{x,r} \|x\|_2^2 + \|r\|_2^2 \quad (4)$$

subject to $G_m x + D_2 r = y_m, 0 \leq x \leq \max y_n$.

In (4), r is a regularization parameter and D_2 is a column-vector indicating the relative accuracy¹ required for satisfying each row of $G_m x + D_2 r = y_m$. The problem solution returns an estimate \hat{x} of the link-level parameters x ; in this work, we obtain the estimates of y_n simply by using the relation $\hat{y}_n = G_n \hat{x}$. The constraint $0 \leq x \leq \max y_n$ ensures that the estimated link-level parameters x are non-negative² and that no link-level parameter can be greater than the largest end-to-end parameter (since end-to-end parameters are sums of link-level parameters). Problem (4) is thus a non-negative linear least-squares problem, which can be solved by using software packages such as PDCO [35]. In terms of scalability, the ℓ_2 -min complexity is $O(aE^3)$, where a depends on the required accuracy on the estimates of x (4) [36]. Thus, with ℓ_2 -min, the path computation time is dominated by the number of links in the network.

¹In the simulation section, we used $D_2 = 1$ where 1 is a column-vector in which each element is equal to 1. This corresponds to the case, without loss of generality, where all constraints in (4) bear the same weight.

²It is assumed non-negative residual dispersion for each link.

In the estimation procedure, we estimate the QoT for unobserved lightpaths given the QoT of the observed lightpaths, and information about the (spatial) correlation structure between the QoT parameters for different lightpaths. The existence of the linear relationships $y_m = G_m x$ and $y_n = G_n x$ ensures that we can use the NK and ℓ_2 -min procedures to estimate y_n given $G_n, G_m,$ and y_m . This estimation procedure is run in turn for R, P, D and Φ . QoT is then computed from the estimated parameters as described in Section II.

III. LIGHTPATH ESTABLISHMENT EXPLOITING ESTIMATION FRAMEWORKS

Four lightpath establishment techniques are proposed:

- *lightpath establishment with distributed network kriging framework scheme (D-NKS)* is proposed for a distributed path computation scenario, and it exploits the NK framework (see Section III-A).
- *lightpath establishment with distributed ℓ_2 -min framework scheme (D-LMS)* is proposed for a distributed path computation scenario, and it exploits the ℓ_2 -min framework (see Section III-A).
- *lightpath establishment with centralized network kriging framework scheme (C-NKS)* is proposed for a PCE-based scenario, and it exploits the NK framework (see Section III-B).
- *lightpath establishment with centralized ℓ_2 -min framework scheme (C-LMS)* is proposed for a PCE-based scenario, and it exploits the ℓ_2 -min framework (see Section III-B).

In order to guarantee QoT, it is assumed that each node is capable of monitoring R, P, D, Φ [17], [25], [27]. The following subsections detail the proposed schemes for both distributed and PCE-based path computation scenarios.

A. Distributed path computation

In distributed path computation each ingress node is responsible for the path computation. Each node stores the GMPLS *traffic engineering database (TED)* with topology and bandwidth information, and a local *measurement database (MDB)* containing the performed end-to-end measurements R_m, P_m, D_m and Φ_m . The MDB is filled through signaling protocol extensions [15]. Hence, each node has its own view of the network's physical layer parameters: two different nodes contain information about different sets of lightpaths (i.e., the ones that cross it).

Fig. 2 summarizes the D-NKS and D-LMS operations. D-NKS and D-LMS only differ in the exploited QoT estimation framework, which are NK and ℓ_2 -min, respectively. Upon a lightpath request from source s to destination d (LP_d in Fig. 2), the ingress node s computes a path q to d . Then, s exploits its local MDB to estimate the QoT of the lightpath if routed along q (1st step). If the QoT parameters of the lightpath, routed

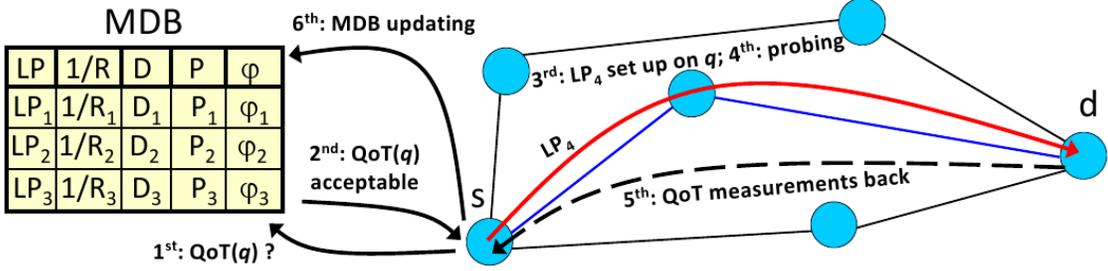


Figure 2. Lightpath establishment operations in a distributed scenario with D-NKS and D-LMS.

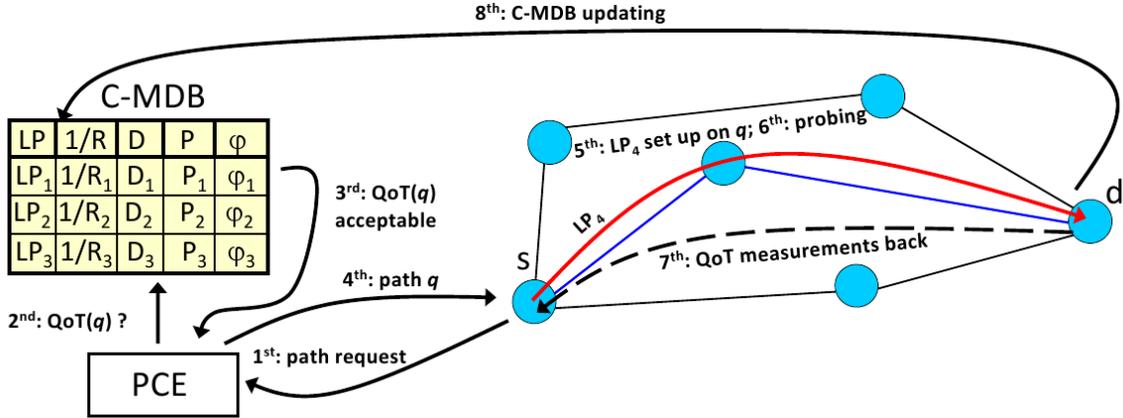


Figure 3. Lightpath establishment operations in a PCE-based scenario with C-NKS and C-LMS.

along q , are already present in the MDB because of previous monitoring, the QoT is computed from data available in the MDB. Otherwise, by applying NK (i.e., D-NKS) or ℓ_2 -min (i.e., D-LMS) to the parameters contained in the MDB (R_m , P_m , D_m and Φ_m), the parameters related to the unobserved lightpath q are estimated and the QoT is derived. If the estimated QoT is unacceptable, another path is computed and the QoT estimation step starts again for the new path. Otherwise (2nd step), s starts signaling along q , to set up the lightpath (3rd step). In the case the estimated QoT is unacceptable up to K paths are considered. If each computed path has an estimated unacceptable QoT, the path with the highest QoT is selected. During the signaling session, link resources (i.e., a common wavelength along all links of q) are reserved and optical cross-connects configured. To verify that the lightpath QoT is acceptable, probing is performed and QoT measurements (all four parameters R , D , P , Φ) are gathered at d (4th step), which sends the measured values back to s (5th step). Each node along q (e.g., s in 6th step) fills the MDB entry related to q with the updated end-to-end measurements. If the measured parameters indicate an unacceptable QoT, s releases resources along q and performs another set up attempt. Otherwise, the lightpath is activated and data transmission begins.

B. PCE-based path computation

In PCE-based computation the PCE stores a database with topology and bandwidth information and a *centralized measurement database (C-MDB)* containing the end-to-end measurements R_m , P_m , D_m and Φ_m from all the previously attempted lightpath set up. Thus, the PCE has a global view of the past probing measurements. Currently, the Internet Engineering Task Force (IETF) is discussing how to maintain information (as updating a database containing QoT information) in databases exploited by the PCE [13], however, this activity is outside the scope of the paper.

Fig. 3 summarizes the C-NKS and C-LMS operations. C-NKS and C-LMS only differ from the exploited QoT estimation framework, which is NK and ℓ_2 -min, respectively. Upon lightpath request from source s to destination d (LP_4 in Fig. 3), path computation is requested to the PCE (1st step), which computes the path q . Then, the C-MDB is exploited to estimate lightpath QoT considering q (2nd step). If the C-MDB holds the QoT parameters for the computed path q from previous monitoring, then QoT is derived from those parameters. Otherwise, by applying NK (i.e., C-NKS) or ℓ_2 -min (i.e., C-LMS) to the parameters (R_m , P_m , D_m and Φ_m) contained in the C-MDB, the parameters related to q are estimated and the QoT is derived. If the estimated QoT is acceptable (3rd

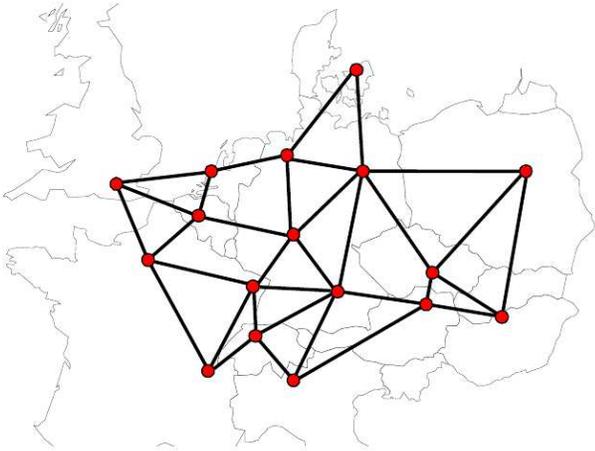


Figure 4. Network topology.

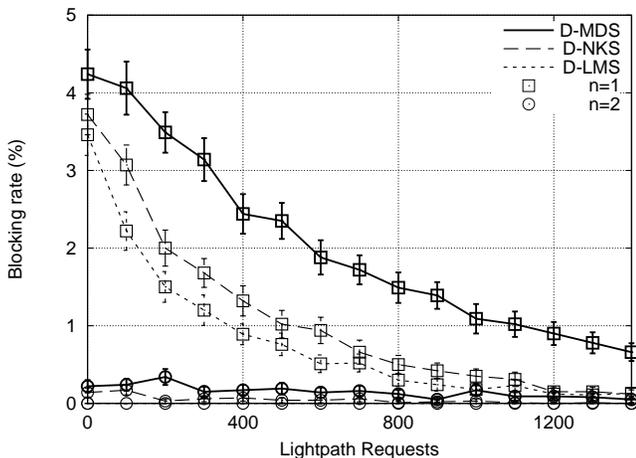


Figure 5. Temporal evolution of the instantaneous blocking rate after $n \in \{1, 2, 3\}$ set up attempts in the distributed path computation scenario.

step), PCE sends the computed path information (e.g., list of nodes) to s (4th step), otherwise another path is computed. Up to K paths can be considered. In case the estimated QoT is unacceptable for each computed path, the path with the highest QoT is selected. Then, s starts signaling along q (5th step), and link resources (i.e., a wavelength along q) are reserved and optical cross-connects configured. To verify that the lightpath QoT is acceptable, probing is performed and QoT measurements are gathered at d (6th step). Then, d sends the measured parameters back to s (7th step) and updates the measured values in C-MDB (8th step). If the measured parameters indicate an unacceptable QoT for q , resources are released along q and another set up attempt is performed. Otherwise, the lightpath is activated and data transmission begins.

IV. CASE STUDY

The proposed lightpath establishment techniques are evaluated by means of a custom event-driven simulator. We consider a Pan-European network (Fig. 4)

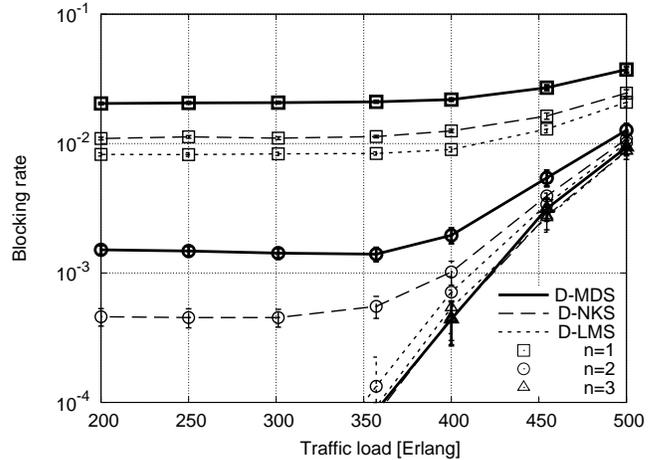


Figure 6. Blocking rate after $n \in \{1, 2, 3\}$ set up attempts for a varying load in the distributed path computation scenario.

with 17 nodes, 33 bidirectional links with 40 wavelengths in each direction. 10 Gbit/s OOK transmission and direct detection are considered. Fixed worst-case margins accounting for non-modeled effects are assumed to be 6dB as in [15]. Lightpaths demands arrive following a Poisson process (average inter-arrival time: $1/\lambda$) and call durations are exponentially distributed (with mean $1/\mu = 2500$ s) such that the total offered load in the network, in Erlang, is λ/μ . Upon lightpath request from source s to destination d , s (if the distributed path computation is utilized) or the PCE (if centralized path computation is utilized) randomly selects a path q within a set $\mathcal{P}(s, d)$ of pre-computed paths. $\mathcal{P}(s, d)$ is the set of all paths connecting s and d that are within one hop from the shortest path. Wavelength assignment is first fit.

To evaluate D-NKS, D-LMS and C-NKS, C-LMS, we also disable the estimation frameworks (i.e., NK and ℓ_2 -min) and we call the resulting establishment techniques *distributed measurement database based scheme (D-MDS)* and *centralized measurement database based scheme (C-MDS)*, respectively in the distributed and in the PCE-based scenarios. With D-MDS and C-MDS, only measurements respectively from the MDB and the C-MDB are used to determine lightpath QoT. Therefore, NK and ℓ_2 -min are not exploited with C-MDS and D-MDS to estimate QoT parameters related to non-observed lightpaths, and we use D-MDS and C-MDS as benchmarks. The actual optical layer performance is emulated considering the model in [15]. The proposed lightpath establishment techniques are compared in terms of blocking rate after a variable number of set up attempts n : blocking occurs if no wavelength can be found on any path in the set $\mathcal{P}(s, d)$ (i.e., *wavelength blocking*) or if the monitored QoT parameters (using probing, after establishment) indicate unacceptable lightpath QoT (i.e., *QoT blocking*). In case of blocking, the successive set up attempt is performed along the maximally link-

disjoint path within $\mathcal{P}(s, d)$.

For each scenario (centralized and distributed), we investigate: the blocking of the lightpath establishment techniques as a function of time (expressed as the number of lightpath requests), the overall blocking rate versus traffic load, and the path computation time. The blocking behavior as a function of the number of lightpath requests is evaluated for a given load, by establishing a number of lightpaths, and assessing the “instantaneous blocking rate”, that is, the blocking rate computed over a small number of lightpath requests using a sliding window average. When the network starts, databases are empty and estimation techniques fail, resulting in high instantaneous blocking rate. However, as more lightpaths are established, the databases fill in and the estimation frameworks are able to decrease the instantaneous blocking rate compared with cases where no estimation framework is leveraged. The instantaneous blocking rate decreases until converging to a floor, in the steady-state.

A. Distributed path computation

In this subsection, D-NKS, D-LMS and D-MDS are compared. We study the behavior of the blocking rate for each of D-NKS, D-LMS and D-MDS as new lightpath requests arrive in the network. This is illustrated in Fig. 5. The figure shows the “instantaneous blocking rate” obtained for a fixed load (200 Erlang, low enough such that blocking is due to QoT only) after $n \in \{1, 2\}$ set up attempts along alternate routes as a function of time, that is, the blocking rate is measured after a varying number of lightpath requests. The plotted results are obtained by averaging 100 randomly generated sequences of lightpath requests and the blocking rate is computed for a sliding window containing the last 100 requests. Up to 3 set up attempts are admitted for each lightpath request. However, blocking rate for $n = 3$ is not reported since, at this load, the blocking rate is always null. As expected, the instantaneous blocking rate decreases while n increases since further set up attempts along alternative paths discovery paths characterized by an acceptable QoT. With each technique, as the MDB is populated, more information is gathered and the instantaneous blocking rate decreases with lightpaths demands. Convergence is faster for D-NKS and D-LMS, because they are able to better exploit the information contained in the MDB than D-MDS thanks to the estimation of the end-to-end parameters. D-LMS obtains better performance than D-NKS. For instance, if a single set up attempt is considered, D-MDS achieves a 1%-instantaneous blocking rate after the arrival of 1200 lightpaths, as opposed to only 600 arrivals for D-NKS and 400 for D-LMS.

Fig. 6 shows the blocking rate after $n \in \{1, 2, 3\}$ attempts as a function of the traffic load when 1500 lightpath demands are generated. Each point is obtained by averaging 100 independent trials of 1500

lightpath requests each. In the range [200,300] Erlang, only QoT blocking is experienced. In this range, D-MDS and D-NKS experience a constant blocking probability for $n \in \{1, 2\}$. Indeed, within 1500 requests, the MDB is not completely filled in case of D-MDS, or, in the case of D-NKS, NK does not have enough information to provide confident estimations for every (s, d) pairs. D-NKS obtains better performance than D-MDS for $n = 1$ and $n = 2$. If $n = 2$ D-LMS obtains a null blocking within the range of [200,300] Erlang since ℓ_2 -min better exploits information in MDB than NK. For all the techniques and for loads higher than 350 Erlang, wavelength blocking becomes significant and blocking increases with load.

To clarify the performance of D-MDS, D-NKS, and D-LMS, Table I shows the data related to a single simulation experiment. Table I contains the real and the estimated values of each QoT parameter, the real and the estimated lightpath QoT (i.e., acceptable or unacceptable) for two sample paths. In particular, Table I aims to: (i) show when a set up attempt is performed along paths with a real unacceptable QoT, and thus when a further set up attempt is required; (ii) provide a qualitative understanding on the better performance achieved by D-LMS with respect to D-NKS in terms of blocking probability. The two sample paths q_1 and q_2 , which have not been monitored, connecting the same pair (s, d) are considered. m_s lightpaths traversing s have been observed and related parameters are stored in the MDB at node s . The real QoT of q_1 and q_2 are acceptable and unacceptable, respectively. With D-MDS no estimation is performed and probing is always performed along the computed path. In this case a further set up attempt is required if the attempted path is q_2 with D-MDS. On the contrary, the lightpath is established if the chosen path is q_1 . When few entries are available in the local MDB (e.g., when $m_s = 6$), QoT is estimated to be acceptable with NK (i.e., probing is performed with D-NKS) for both q_1 and q_2 , and thus a further set up attempt is required if q_2 is first selected. On the same scenario (i.e., when $m_s = 6$), ℓ_2 -min tends to be more pessimistic and QoT is estimated to be unacceptable for both q_1 and q_2 . In this case, the path with the higher QoT (q_1 in this case) is probed, and no further set up attempt is required with D-LMS. Estimation accuracy increases with the number of observations (e.g., with NK $1/R$ is estimated to be 0.007 and 0.026, when $m = 6$ and $m_s = 34$, respectively, while the actual $1/R$ is 0.034). For instance, when the local MDB includes numerous entries (e.g., $m_s = 40$) also with D-NKS, probing is avoided along q_2 , which presents actual unacceptable QoT.

The path computation time required by each scheme has been evaluated by considering the actual path computation time experienced during the simulations presented in Fig. 5. The simulations have been run on a Pentium Intel Q8200 at 2.33 GHz. With D-MDS,

Table I
REAL AND ESTIMATED QoT PARAMETERS, AND REAL AND ESTIMATED LIGHTPATH QoT FOR TWO SAMPLE PATHS WHEN m_s
OBSERVATIONS ARE AVAILABLE AT s

q	$1/R$			D [ps/nm]			P^2 [ps ²]			Φ			real QoT	estimated QoT		
	real	NK	ℓ_2 -min	real	NK	ℓ_2 -min	real	NK	ℓ_2 -min	real	NK	ℓ_2 -min		D-MDS	D-NKS	D-LMS
q_1 $m_s = 6$	0.034	0.007	0.053	41	10.25	26.98	92.99	21.28	49.25	0.044	0.009	0.064	acc.	none	acc.	un.
q_2 $m_s = 6$	0.040	0.007	0.06	51.25	10.25	32.55	99.7	21.28	58.57	0.04	0.009	0.08	un.	none	acc.	un.
q_1 $m_s = 34$	0.034	0.026	0.046	41	31.12	34.23	92.99	71.18	74.7	0.044	0.034	0.050	acc.	none	acc.	acc.
q_2 $m_s = 40$	0.040	0.040	0.040	51.25	51.25	51.25	99.78	99.78	99.78	0.047	0.047	0.047	un.	none	un.	un.

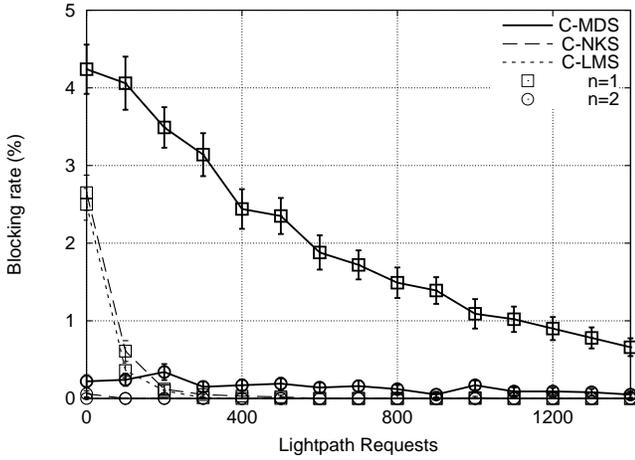


Figure 7. Temporal evolution of the instantaneous blocking rate after $n \in \{1, 2, 3\}$ set up attempts in the PCE-based scenario.

path computation time can be considered negligible (less than 10^{-5} s). On average, in case of D-NKS and D-LMS, a lightpath path computation requires 0.4 ms and 107 ms, respectively. It is expected that the path computation time in a real transparent network does not increase since all-optical networks with significantly higher number of nodes and links are unlikely to be set up because of impairment accumulation along lightpaths.

B. Centralized PCE-based path computation

In this subsection, C-NKS, C-LMS and C-MDS are compared. As before, we first study the behavior of the instantaneous blocking rate for each of C-NKS, C-LMS and C-MDS. Fig. 7 shows the behavior of the instantaneous blocking rate for C-NKS, C-LMS and C-MDS as new lightpath requests arrive in the network. Up to $n = 3$ lightpath establishment attempts are allowed. The total offered load is set to a low value, 200 Erlang, such that wavelength blocking is negligible compared with QoT blocking. As new demands arrive, the C-MDB is populated, allowing C-MDS to know the QoT for an increasing number of lightpaths, and allowing C-NKS and C-LMS to estimate QoT more accurately, resulting in a decrease of the instantaneous

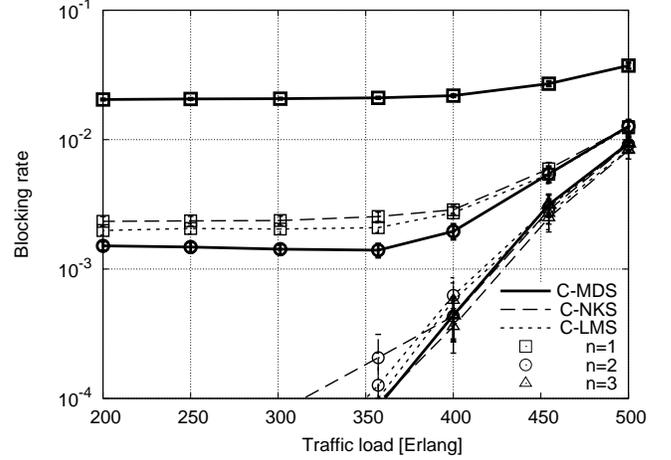


Figure 8. Blocking rate after $n \in \{1, 2, 3\}$ set up attempts for a varying load in the PCE-based scenario.

blocking rate even for $n = 1$. For instance, C-NKS and C-LMS obtain a null blocking with $n = 1$ after 300 lightpath requests, while C-MDS takes 1400 lightpath requests and a second attempt ($n = 2$) per lightpath demand to achieve a null blocking.

Fig. 8 shows the establishment of 1500 lightpaths for a varying offered load in the network after $n \in \{1, 2, 3\}$ set up attempts. Blocking rate decreases when the allowed number of set up attempts increases. Blocking increases with traffic load since wavelength blocking contributes at high loads. Contrary to C-MDS, C-NKS and C-LMS leverage the estimation frameworks and is seen to strongly decrease the number of required set up attempts to successfully establish lightpaths, compared with C-MDS. In particular, the blocking probability is much lower with C-NKS and C-LMS than C-MDS for $n = 1$. C-MDS obtains with $n = 3$ the same blocking probability that C-NKS and C-LMS obtain with $n = 2$. For instance, for a load of 400 Erlang, C-MDS requires 3 lightpath set up attempts to achieve a blocking rate lower than 10^{-3} , while C-NKS and C-LMS require only 2 attempts.

To assess the path computation time, we implemented the simulated PCE on the same PC of the previous section. With C-MDS, path computation time

Table II
BLOCKING RATE (%) AFTER n SET UP ATTEMPTS AND k LIGHTPATH REQUESTS

n	k LP requ.	C-MDS	D-MDS	C-LMS	D-LMS
1	100	4.06	4.06	0.36	2.22
1	400	2.42	2.44	0	0.89
2	100	0.23	0.24	0	0
2	400	0.17	0.17	0	0

can be considered negligible as in the distributed scenario. On average, in case of C-NKS and C-LMS, a lightpath path computation requires 103 ms and 137 ms, respectively. In terms of absolute values, a centralized PCE is expected to operate on powerful dedicated CPUs, thus potentially increasing the computational speed with respect to the distributed case.

C. Distributed versus Centralized PCE-based scenarios

Table II reports an extract of Figs. 5 and 7. The comparison between the distributed and the PCE-based centralized schemes highlights that without QoT parameters estimation (i.e., D-MDS and C-MDS) no advantage is provided in terms of blocking probability by the centralized knowledge of QoT information. Indeed, with D-MDS and C-MDS, just the QoT parameters (if available) of the selected lightpath (by the ingress or by the PCE, respectively) are exploited. Only if the lightpath has been already monitored, such information is available with both schemes. Blocking probability results confirm that, at different set up attempts or upon different amount of offered lightpath requests, D-MDS and C-MDS provide the same results. On the contrary, if QoT parameter estimation is introduced, e.g. when ℓ_2 -min framework is applied, results show that at the first set up attempt (i.e., $n = 1$), C-LMS scheme provides significant advantage with respect to D-LMS by exploiting a larger amount of QoT parameter information. For example, as shown in Table II, upon 100 requests D-LMS and C-LMS provide a blocking rate of 2.22% and 0.36% respectively. Upon 400 requests, the two schemes still perform differently, achieving a null blocking rate and a blocking less than 1% with C-LMS and D-LMS, respectively. In addition, as early as at the second set up attempt (i.e., $n = 2$), both C-LMS and D-LMS achieve optimal results, i.e. null blocking rate.

V. CONCLUSIONS

By combining monitoring hardware and end-to-end estimation frameworks, we showed that it is possible to estimate the QoT for a lightpath before it is established, thereby avoiding set up attempts for lightpaths with (estimated) low QoT. We investigated the utilization of two end-to-end estimation frameworks: network kriging and norm ℓ_2 minimization. The exploitation of these estimation frameworks during lightpath establishment may be applied for both

distributed path computation and centralized PCE-based network scenarios. A practical consequence of the proposed techniques is that, for a given target blocking rate, fewer establishment attempts are required thanks to the estimation step. For instance, in a distributed network scenario, the utilization of end-to-end estimation decreases the number of required establishment attempts from 3 to 2 to achieve a given target blocking rate of 10^{-3} . We also showed that the lightpath establishment schemes assisted with end-to-end estimation converge faster in terms of blocking rate, than the schemes where no end-to-end estimation is performed. This has an important practical implication: estimation-based schemes are more reactive to assist dynamic transparent networks of the future. We observed that the exploitation of the ℓ_2 -min yields better performance than network kriging in terms of blocking probability, particularly in the case of the distributed scenario. In a PCE-based scenario, the exploitation of network kriging or norm ℓ_2 minimization induces more benefits in terms of blocking probability than with the distributed scenario when limited QoT information is available. Indeed, a centralized database holds significantly more information that can be better exploited by the estimation frameworks than in the distributed scenario, thus reducing the average amount of required lightpath set up attempts. However, particularly in the case of network kriging, better performance in terms of required path computation time is achieved in the distributed with respect to the centralized scenario. In the centralized PCE-based scenario the average performance in terms of required path computation time are comparable between network kriging and ℓ_2 -min, while in the distributed scenario network kriging outperforms the other one.

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