Cross-Layer Control of Semi-Transparent Optical Networks under Physical-Parameter Uncertainty

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Abstract This work deals with the *Routing and Wavelength Assignment and Regenerator Placement* (RWARP) in semi-transparent optical networks. In particular, it focuses on semi-transparent network dimensioning and control, exploiting a cross-layer approach. The chapter describes the physical model adopted and the *deterministic* RWARP algorithm proposed for the dimensioning phase, computing the necessary resources of the network. Moreover the *deterministic* algorithm and a new RWA algorithm based on prediction concepts are proposed to analyze the network response in different conditions, in terms of parameter values of the systems and offered traffic. Results of this analysis show that the *deterministic* approach performs better in case of perfect knowledge of the impairment parameters, while the predictive one outperforms the former in case of imperfect knowledge, which is usually the case in practical settings.

1 Introduction

Optical Transport Networks (OTNs) based on Wavelength-Division Multiplexing (WDM) have achieved today a high degree of maturity. With the extremely rapid growth of Internet traffic generated by new applications (e.g. cloud computing, datacenter interconnection, etc.) and subscriber needs, a new challenge awaits OTN: that is the capability of scaling-up in capacity, while keeping cost and required energy per transported bit at the same level or even lowering them.

It is well recognized that one of the major limitations in this process is represented by the optical-signal regeneration. This function is needed to overcome signal degradation due to several impairments which accumulate as light propagates through a network. Effects to be compensated are: loss, Amplified Spontaneous Emission (ASE) noise, chromatic and polarization-mode dispersion, filter cascading, non-linear effects such as four-wave mixing, self- and cross-phase modulation, Brillouin and Raman scattering. They are particularly severe in high-bitrate and long-haul Dense-WDM (DWDM) systems.

Since all-optical regeneration is still mainly a research topic, the opto-electronic regenerator (also known as "*transponder*") is the most commonly-adopted solution: this device converts signals from optical to electronic form, regenerates, and converts back to optical. The double conversion from optical to electronic and back to optical (OEO conversion) is highly power-consuming. Moreover, although transponders are less expensive than all-optical regenerators, they still are among the most expensive network elements of an OTN.

In order to save on CAPEX, regeneration capability can be sparsely provided in the network, installing transponders where needed, possibly trying to minimize their number. Networks in which this strategy is adopted are called "*semi-transparent*" (alias "translucent"). Off-line planning of a semi-transparent network requires deciding where to deploy transponders in an optimal way, on the basis of a given forecast traffic demand. Once the network is in operation, the on-line Routing and Wavelength Assignment (RWA) process of a new connection has to take into account the location of the available regeneration points.

With semi-transparent OTNs both off-line design and on-line RWA become cross-layer problems coupling the physical layer, where constraints due to transmission impairments are generated, to the logical layer, which manages the optical end-to-end connections (lightpaths). Cross-layer design and routing techniques are generally quite complicated: in our case, they are even more complex especially due to the difficulty in modeling some optical transmission impairments, as for instance those caused by non-linear effects in light propagation.

The first part of this chapter is preliminary. We present a design method to perform off-line planning and regenerator-placement in a semi-transparent OTN. Network resources are dimensioned and transponders are properly installed in order to support a given set of static connections, while guaranteeing that the signal quality at the receiver is above a fixed threshold for each connection. The method relies upon a semi-empirical model of the physical layer, which requires a few input parameters describing the optical DWDM transmission systems to estimate the propagation impairments.

The second part of the chapter contains the main idea. We propose two different RWA algorithms for on-line connection control. The first (named "deterministic") bases its routing decisions upon the knowledge of the input parameters of the physical-layer model. The second (called "predictive") selects the routes for the lightpaths on a topological basis, "agnostically" of the physical layer, but selflearns from successes and failures when signal quality of the routed connections is compared a posteriori to the fixed threshold.

The main focus of the study we are presenting in this chapter is to investigate the behavior of the two RWA algorithms when the input-parameters of the physical-layer model are affected by *uncertainty*, i.e. they do not faithfully represent the real state of the network. In fact methods to provide the input values to the parameters (e.g. inference from data-sheets) and to keep such values updated (e.g. in-field measurements) may lead to deviations between the actual state and the model, which can potentially jeopardize cross-layer design and control. This is an important issue which has been up to now only covered by a few studies (see e.g. [1], which focuses on in-field measurement of physical-layer parameters). Our novel contribution to this topic is the identification of two possible ways in which uncertainty about the physical-layer state can manifest:

- **imperfect matching**: model input-parameter values used in the planning phase are different from the actual values. This may occur, for example, because: network design relied upon a nominal set of values declared in data-sheet components which revealed to be too optimistic: the design was done long time ago and aging has worsened equipment behaviour; the model adopted for the physical layer does not represent all relevant impairments or is not accurate enough, etc.;
- **imperfect knowledge**: model input-parameter values used by the control system, and in particular for routing connections, deviate from the actual values. This may happen, for example, because: values are provided to the control-plane by periodic measurements that are either affected by errors or too infrequent to correctly sample parameter variations, the physical model adopted by the control plane does not represent all relevant impairments or is not accurate enough, etc. Our physical model does not take into account inter-channel effects such as the crosstalk.

We have simulated on a case-study network combinations of imperfect matching and knowledge in order to compare the behavior of the two RWA algorithms. As will be apparent form the results of our dynamic-traffic simulations presented at the end, the deterministic algorithm achieves the best results in ideal conditions, but the predictive is more robust to uncertainty, providing remarkable advantages, especially when imperfect matching and knowledge jointly occur. Thus in a realistic scenario a network operator should choose to rely for RWA computation on detailed and accurate physical-layer information or rather to rely on prediction according to the confidence the operator has on physical-layer parameters.

The outline of this chapter is as follows. Section 2 is dedicated to network design, illustrating the physical-layer model we have adopted based on the Personick Q factor. Section 3 deals with network control, presenting the two algorithms for semi-transparent cross-layer routing we are proposing and comparing. This section also defines the different uncertainty scenarios we have considered. Section 4 shows and comments on the results of the case-study by which we have compared the behavior of the routing algorithms under the uncertainty conditions presented in Section 3.

2 Semi-transparent optical network design

The problem of network design for a semi-transparent OTN can be defined as follows. The topology of the network in terms of switching nodes and links is given. Requirements are set by providing the features of the traffic that has to be supported by the network. The final purpose is to dimension network resources (transmission resources and regenerators), so that traffic requirements are met under the constraints (propagation impairments) imposed by the physical layer.

Recent studies have been dedicated to modeling transmission impairments, both linear and non-linear; the reader is referred to [1] to [7]. A physical-layer impairment model must be simple enough to be usable. Namely, a limited number of input parameters should be sufficient to characterize each optical link; then, a single output parameter should be used to represent the effects of all the considered impairments on each optical circuit: see [8][9] and [10]. Many works adopt the *Personik Q factor*[1] (see Section 2.2) as single output parameter [8]. OTN design under physical impairments – intended as network dimensioning and regenerator placement for a given static-traffic demand – has been treated by different works, like [9], [10], and [8].

However, all these previous proposals consider that the physical information is completely accurate. Few recent works in the literature deal with the modeling/dimensioning and routing taking into account the possible inaccuracy in the physical information. In [11] a method is proposed, based on *Q* factor and Optical Signal to Noise Ratio (OSNR) measurements, to compute the error (or inaccuracy) associated with each link on the network. Authors in [12] propose a physical model that interpolates the Bit Error Rate (BER) from experimental measurements. This interpolation introduces uncertainties which have to be considered when evaluating the feasibility of a lightpath. In [13], these uncertainties are considered by means of an extra fixed margin. A lightpath is only considered feasible if its *Q* factor, is higher than a threshold plus this extra fixed margin. This fixed value is computed from the standard deviation of the difference between the real BER and the interpolated BER values. Finally, in [14] this extra margin is proposed to be variable and it is based on the amount of residual chromatic dispersion and non-linear phase experienced by the signal.

The following two sections explain how we model the *lightpath* and *physical layers*.

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[1] From this point on we will indicate the Personik *Q* factor with the abbreviation *Q factor*.

2.1 Optical-circuit layer model

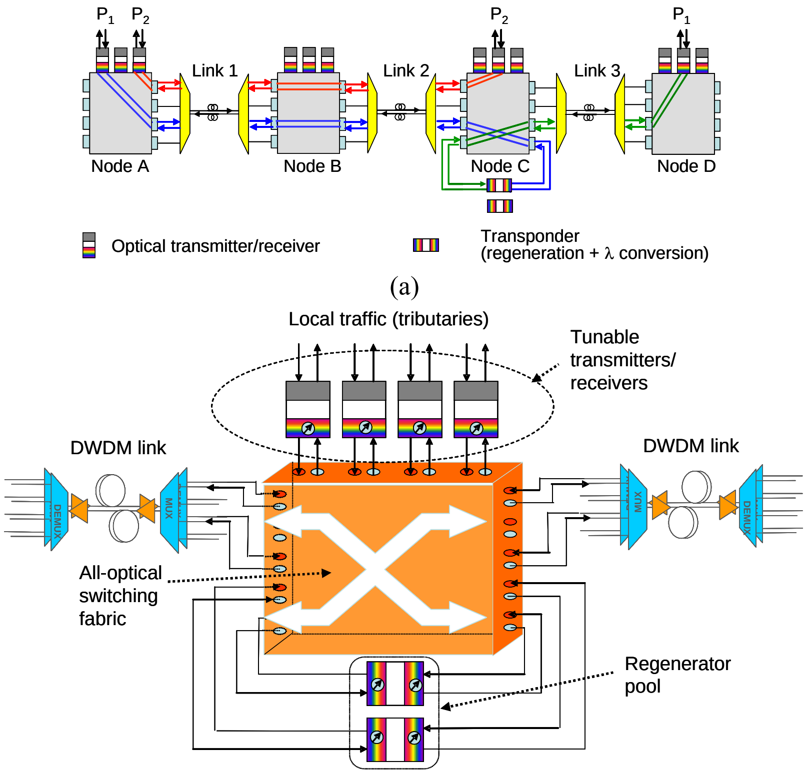
In optical-circuit-switched networks the basic managed entity is the *lightpath*, an end-to-end optical connection between a source and a destination node, requiring one wavelength-channel per network link crossed. Traffic is defined by a matrix of demands between the node-pairs of the network. In our design problem we have assumed that traffic is static (all connections are permanent) and lightpaths are unprotected (the protected case will be considered in Chapter 9).

Each network link is equipped with a certain number of DWDM *transmission systems* (the details of the DWDM transmission systems will be specified in Section 2.2). We have assumed that all the DWDM systems in the network are equal and provide the same pre-assigned maximum number of WDM channels W. The network-design procedure determines how many DWDM systems have to be installed on each link to support a given traffic.

The type of approach to regeneration adopted in an OTN has a deep impact on the complexity of the planning problem.

In most OTNs (so called "*opaque*") each optical link of the network is terminated at both ends by optoelectronic interfaces hosted in the nodes. This approach simplifies network management, design and control, as it implies a full independence of the logical layer from the physical layer. Each optical transmission system can be engineered separately, regardless of traffic conditions. Also the network at the optical-circuit layer can be optimized regardless of the physical-layer transmission impairments. As OEO converters jointly perform regeneration and wavelength conversion, the two problems of wavelength assignment and of routing are also decoupled. Actually, the particular channel assignment of a connection on a specific link becomes a link local problem, hence only routing has to be planned network-wide for each connection. The design problem is not substantially different from a classical transport network (e.g. SDH).

At the opposite extreme of the opaque approach, we have the *fully transparent* OTN. With optical transparent switching, OTN design and operation become cross-layer problems coupling the physical to the logical layer: transmission impairments and wavelength assignment have to be taken into account when the lightpath is setup and routed across the network, as well as transmission systems have to be planned on the basis of a given traffic demand. All-optical wavelength converters, as the all-optical regenerators, are not yet commercially-available products. Thus in a *fully-transparent* OTN, we can assume that no wavelength conversion is allowed, and thus Routing and Wavelength Assignment (RWA) has to be found for each lightpath during the network-design procedure. Transmission impairments limit the maximum distance reachable from the source node and thus the geographical extension of the network.



(a)

(b)

Fig. 1. a) Semi-transparent network: routing a connection in wavelength continuity (red) or with regeneration and wavelength conversion (blue/green). b) Node model for a semi-transparent network.

Eliminating OEO conversions completely from the network is possible only for limited-size plants. In most wide-area networks, the only viable option is the *semi-transparent* approach. The regenerators break up the optical continuity of those lightpaths that would be impossible to setup in transparency. Semi-transparency is likely to be preferable also in smaller networks for control and monitoring reasons, at least until such functions be all-optically available. A regenerator completely restores the quality of the signal along a lightpath, as if it were back-to-back to the transmitter. Regenerators are available only at the network nodes. It should be noted that an opto-electronic regenerator is also able to operate as a wavelength converter.

In the example of Fig. **1. a) Semi-transparent network: routing a connection in wavelength continuity (red) or with regeneration and wavelength conversion (blue/green). b) Node model for a semi-transparent network**a, while lightpath $\mathbf{P_2}$ can be setup transparently, lightpath $\mathbf{P_1}$ needs at least a regenerator point. A regenerator is thus installed in node C (enlarged in Fig. **1. a) Semi-**

transparent network: routing a connection in wavelength continuity (red) or with regeneration and wavelength conversion (blue/green). b) Node model for a semi-transparent networkb), splitting $\mathbf{P_1}$ into two sub-paths. The regenerator is also used as a wavelength converter. In general when a regenerator is necessary on a path there may be several options for its placement. For instance, in the example of Fig. **1. a) Semi-transparent network: routing a connection in wavelength continuity (red) or with regeneration and wavelength conversion (blue/green). b) Node model for a semi-transparent network**a, the regenerator could be installed in node B instead of node C.

In conclusion, designing a semi-transparent network implies three problems to be solved under constraints from the transmission layer: Routing, Wavelength Assignment, and Regenerator Placement (RWARP). Section 3.3 presents our design algorithm which jointly solves the three problems.

2.2 Physical layer model

An optical signal is subject to impairments (linear and non-linear) which degrade its quality as it transparently propagates through the network: the physical-layer model allows us to relate such degradation to the physical parameters of the network elements crossed along the path. Our model is based on two network elements: the optical switching-node and the optical transmission system. In a semi-transparent OTN the *optical-switching nodes* are the sites where transmitters, receives and regenerators are located (see Fig. **1. a) Semi-transparent network: routing a connection in wavelength continuity (red) or with regeneration and wavelength conversion (blue/green). b) Node model for a semi-transparent network**b). The core of the node is a non-blocking all-optical switching fabric, assumed to introduce only attenuation (crosstalk, i.e. interference between WDM channels within the node is neglected in this work).

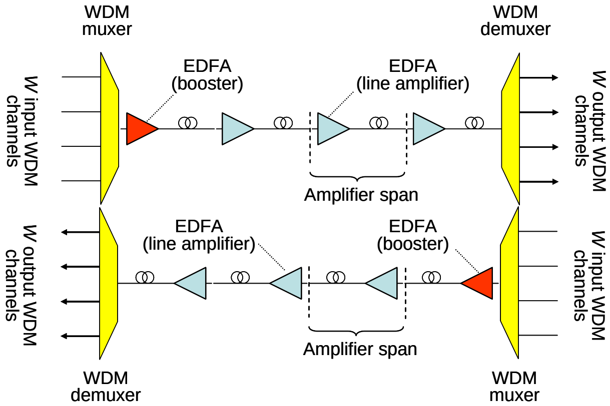


Fig. 2. DWDM transmission system.

Each *optical transmission-system* (Figure 2) is bidirectional and composed of: i) a couple of counter-propagating fibers; ii) the set of optical Erbium Doped Fiber Amplifiers (EDFAs) necessary to completely recover loss due to fiber propagation. An optical-amplifier span is the optical-fiber segment connecting an EDFA to the next one or to the end-node of the link. We assume that each EDFA is placed at the beginning of its span. The first EDFA of a link in one direction is located at the output of the source node of the link (i.e., it is used as a booster); all the other EDFAs of a link are used as line amplifiers.

If a connection is unfeasible end-to-end in transparency, a regenerator is added in a transit node and dedicated to the connection: the lightpath is split by each regenerator into two contiguous *transparent sub-paths*. If R_P is the number of regenerators dedicated to a *H*-hop lightpath **P** $(0 \leq R_P \leq H-1)$, then the number of transparent sub-paths composing the lightpath is $R_P + 1$.[2] At the end of each sub-path (except the last one) a regenerator (OEO transponder) renews the signal. In this work we are considering 3R (re-amplification, re-shaping and re-timing) regenerators, which fully restore signal quality as if at the transmitter. Thus, from a signal-impairment point of view, the regeneration operation implies a complete loss of memory of the history of the signal along the path followed to reach the regenerator. The regeneration of a bidirectional WDM channel crossing a node requires four unidirectional (or two bidirectional) node ports and one (bidirectional) regenerator (see Fig. **1. a) Semi-transparent network: routing a connection in wavelength continuity (red) or with regeneration and wavelength conversion (blue/green). b) Node model for a semi-transparent network**b).

The key parameter to measure the signal quality is the BER, which directly contributes to the quality of service perceived by the user of a circuit-switched network: an optical circuit can be set up if the BER at the receiver is above a threshold. A BER threshold translates by well-known relations into a threshold value of the *Q* factor [8], which in turn can be evaluated as a function of the transmission-system parameters and the transmission impairments.

The computation of the *Q* factor can be carried out by different methods, from analysis in the simplest cases, to physical-layer simulations in the most complicated ones. In particular, we have adopted in our model a semi-empirical method proposed in the European Project NOBEL 1 [15] and [17]. The computation of the *Q* factor takes the following impairments into account: ASE, loss (linear); self- and cross-phase modulation (non-linear). The other effects (and in particular, polarization-mode and chromatic dispersions) are not considered.

Let us consider a *h*-hop sub-path **p**, crossing *h* links having lengths $L_{(1,\,p)}$, …, $L_{(\mathrm{h},\,p)}$ from the source to the end node. The *Q* factor at the end of the sub-path is given by the equation:

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[2] If $R_P = 0$ the connection is end-to-end transparently feasible, hence the single sub-path is coincident with the lightpath.

$$Q_p\ [\mathrm{dB}] = a_0 + a_1 OSNR_p + a_2 N_p + a_3 \left(P_0 \cdot N_p\right)^B \qquad \text{Eq. 1}$$

Coefficients a_0, a_1, a_2, a_3 and *B* depend only on the type of DWDM transmission system deployed in the network links. They are evaluated by parametric identification starting from a set of experimental measurements. The third and fourth terms of the equation take non-linear effects into account. P_0 [dBm] is the power level at the sub-path channel-signal launch. N_p is the total number of EDFA-amplifier spans crossed by the sub-path, which is given by: $N_p = \Sigma_{j=1}^{h} \lceil L_{(j,p)} / s \rceil$, where *s* is the maximum span length, and all the spans of a link *j* have equal length $L_{(j,p)} \big/ \lceil L_{(j,p)} / s \rceil$ ($\approx s$ for $L_{(j,p)} >> s$). It is assumed that each span contributes to the non-linear effects.

$OSNR_p$ is the optical signal to noise ratio over a fixed optical bandwidth (dependent on the bitrate and the modulation format of the transmitters):

$$OSNR_p\ [\mathrm{dB}] = P_0 - QN - 10\mathrm{Log}_{10}\left(\sum_{i=1}^{N_p} (1 - x_i) \cdot \alpha\ [\mathrm{lin}] \cdot L_{(i,p)} + x_i \cdot TN\ [\mathrm{lin}] \right) - NF \qquad \text{Eq.2}$$

Where: *QN* is the quantum noise; $\alpha\,[\mathrm{lin}]$ is the fiber loss per km (in linear units); $TN\ [\mathrm{lin}]$ is the loss of the transparent optical-switching matrix of a node (in linear units); *i* indicates the EDFA spans; $x_i = 1$ when *i* is pointing to the last span of each link; $x_i = 0$ otherwise; *NF* [dB] is the noise figure of the optical amplifiers (assumed equal for all the EDFAs, regardless if boosters or line amplifiers). A detailed list of the values used for all the parameters is reported in Section 4.

A minimum threshold value of *Q*, called Q_{min}, is required at the end of each sub-path: $Q_p \geq Q_{\min}\ \forall \mathrm{p}$. If the minimum threshold on the *Q* factor is not satisfied by a sub-path, this has to be further divided into sub-paths by adding other regenerators. Q_{min} is chosen according to the maximum acceptable BER (see Section 4 for numerical values).

2.3 Planning procedure

RWARP is a non-trivial optimization problem (even when performed for a single connection): in fact it contains the Restricted Shortest Path (RSP) as a sub-problem. RSP consists of finding a minimum-cost route satisfying a constraint on some parameter (e.g. delay, noise, *Q* factor, etc.), which monotonically increases (or decreases) with the distance from the source. RSP is known to be NP-complete, and thus, RWARP is at least NP-complete. Compared to RSP, RWARP is surely more complex because the *Q* factor is not monotonic due to the presence of the regenerators along the path. Moreover there is an additional objective function to minimize, i.e., the number of regenerators. Since exact solution-methods are likely to be too complex to be useful in realistic-dimension scenarios, we have adopted a heuristic approach, briefly described in what follows.

Our network planning procedure makes use of the RWARP approach described in [16] and [17]. At the beginning, the network is equipped with one regenerator per node and one DWDM transmission system per link (we recall that all DWDM systems have the same maximum number of WDM channels W). The set of permanent-connection requests provided by the traffic matrix is randomly sorted.[3] Then, requests are processed one by one by the RWARP algorithm, which computes the RWA under the Q factor constraint, trying to minimize the number of regenerators used by the connections and the amount of allocated resources. After serving each request, the nodes with no more free regenerators are provided with one extra regenerator and each link with no more free wavelengths on the already installed DWDM systems is provided with one additional DWDM system. After all connections have been set up, unused regenerators and DWDM systems, if any, are removed.

The RWARP algorithm is based on the definition of a metric that leads to small-length paths using the lowest number of regenerators: the cost of a H-hop path **P**, routed on links having lengths $L_{(1,P)}, \ldots, L_{(H,P)}$, is: $C_P = \sum_i^H L_{(i,P)} + R_P \cdot C_{reg}$, where R_P is the number of regenerators used by **P** and C_{reg} is the cost of a regenerator (normalized to the cost of a unit length of optical link). The metric is additive and can be used in a minimum-cost-path searching algorithm. To do this, each optical cross-connect of the network is represented in an auxiliary graph as three graph nodes: *ingress*, *egress* and *regenerator*. A direct connection (*ingress* → *egress*) corresponds to a transparent bypass, while an (*ingress* → *regenerator* → *egress*) connection means that the lightpath **P** has made use of a regenerator available at the node (splitting **P** into two adjacent sub-paths). C_{reg} is assigned to the graph arc *ingress* → *regenerator*, while the arc *ingress* → *egress* has null cost. Thanks to the metric and to this auxiliary-graph construction a path is sent through a regenerator (increasing C_P) only if this is necessary, i.e., if otherwise the Q factor constraint would be violated. Moreover, in most cases sub-paths are routed in such a way that their Q_p is maximized, since an important component of Q-factor degradation is proportional to the total sub-path length (see Eq. 2) and the first term of C_P tends to minimize the length of each sub-path of a lightpath.

Due to the non-monotonic behavior of the Q factor (because of regenerator crossings), the minimum-cost-path searching algorithm cannot be as simple as Djikstra. The classical version of this algorithm finds the minimum-cost path in a sequence of steps in which at each step a comparison is carried out between two or more candidate paths. By these comparisons, candidate paths are progressively

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[3] Random sorting is the simplest approach. Other more efficient sorting rules will be studied in future work.

discarded, until only one shortest path remains. In our case, candidate paths cannot be immediately discarded simply on the basis of their costs: a more expensive sub-path may become the best solution if the Q factor of the cheapest sub-path falls below the threshold Q_{min}. However, not discarding candidate paths implies that the computational complexity tends to grow exponentially as the network is explored starting from the source node. Luckily, the known concept of *domination* comes into aid: given a H-hop path $\mathbf{P_1}$ and a K-hop path $\mathbf{P_2}$, both from the source-node S to the same intermediate node N, $\mathbf{P_1}$ *dominates* $\mathbf{P_2}$ if $[C_{P_1} \le C_{P_2}$ and $H \le K$ and $Q_{P_1} \ge Q_{P_2}]$. In our algorithm the set of candidate paths from S to N is restricted to the dominating paths, i.e., each time a path of the set is dominated it is discarded[4]. The already-mentioned property that a vast component of Q–factor degradation is proportional to the sub-path length contributes to keep the number of candidate paths relatively low. In conclusion, our RWARP algorithm is a Q-constrained breadth-first-search over non-dominated paths.

3 Semi-transparent optical network control

Let us now focus on the second cross-layer problem in semi-transparent OTNs that is network control. Numerous publications concern the control of transparent and semi-transparent networks in dynamic-traffic conditions and propose various routing and wavelength-assignment algorithms under transmission-impairment constraints [18] [19], and also different extensions to the control plane for encompassing the physical impairments [20] [21].

Our approach to the problem is the following. A semi-transparent network formerly designed for a given static traffic, with RWARP performed for each connection, is now considered under dynamic traffic, with lightpaths set-up and torn-down on demand. Events of request and holding-times are randomly generated (in our case we have assumed a Poisson traffic model, with exponential distribution of both inter-arrival and holding times), but dynamic traffic is not entirely uncorrelated to the original static-traffic matrix used as input for the design phase: in fact we set the parameters of traffic generators so that on average the number of connections requested between each node-pair is the same as in the static case.

As regenerators are already deployed according to the design phase, we assume they can only be used or not used by each dynamic connection, but not added or moved from a node to another. Thus, the control plane performs RWA for each new optical connection. If this operation is successful, the lightpath can be set up and resources for it (one WDM channel for each crossed link and all the **regenerators** it uses) are held for the whole duration of the connection. If RWA is unsuc-

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[4] It should be remarked that discarding dominated paths may occur at each intermediate node N, i.e. we do not need to know the entire paths from source to destination.

cessful, the connection-request is blocked. It should be noted that blocking can occur for two reasons: lack of free resources and lack of free regenerators.

We have proposed two different RWA algorithms that will be presented in the next sections. Then we will introduce the issue of physical-layer parameter uncertainty and how it can affect RWA.

3.1 Deterministic RWA algorithm

The first RWA algorithm we are presenting is *deterministic* in the sense that it makes use of the knowledge of the state of both lightpath and physical layers to take its RWA decisions.

The algorithm is run by the control plane at each occurrence of a connection-request event. In practice it is exactly the same as the heuristic used for the dimensioning phase (RWARP) and presented in Section 2.3, but with the simplification that it is used for one connection at the time, rather than on a set of connections as during planning. The medium complexity makes it more suitable for a centralized control implementation rather than a distributed one.

There are differences in its behavior which can be summarized as follows:

- access to optical regeneration functionality is forbidden in nodes having no free regenerators: regenerators cannot be added;
- connections have a finite duration: when a connection ends, its resources in terms of used wavelengths/regenerators are freed.

If no path can be found guaranteeing the Q-factor quality, then the connection is blocked.

3.2 Predictive RWA algorithm.

The *predictive* RWA algorithm, *Prediction Route according to the Q factor* (PR-Q) [17] takes into account the Q factor and it is also based on the *Prediction-Based Routing* (PBR) [22] mechanism. This PR-Q algorithm does not route the lightpaths minimizing the number of regenerators or maximizing Q (routes are pre-calculated). On the other hand, it is designed to counteract the negative effects of signal-quality information inaccuracy by a self-learning capability. PR-Q utilizes K routes previously computed by means of the *Minimum Coincidence and Distance* (MINCOD) routing algorithm [19].

- MINCOD algorithm exploits the concept of minimum coincidence between paths (a purely topological property) to balance the traffic load, hence reducing the network congestion. MINCOD finds the K-paths from a source to a destination node having minimum distance and fewest shared links. Firstly, it chooses the shortest path (in distance); secondly, it associates a metric to the rest of routes. This metric is named Minimum Shared Link (MSL) and is computed according to Eq. 3, where *DP* is the end-to-end distance of the particular path and *SL* is the number of links shared between this path and the paths selected in previous steps. The MINCOD algorithm selects the next $K - 1$ paths with minimum MSL value.

$$MSL = DP \cdot (1 + SL) \qquad \text{Eq.3}$$

- PR-*Q* algorithm: To implement the predictive mechanism (PBR) [22] *w* two-bit counters are introduced for every sub-path, where *w* is the number of possible wavelengths that can be assigned to the sub-path, i.e. $w = W \cdot \min\{S_{(j,p)}\}$ where $S_{(j,p)}$ is the number of transmission systems installed on link j of the path. The algorithm selects the first route (and wavelength) fulfilling that, the *Q* factor of every sub-path (and wavelength) is higher than $Q_{min,}$ the two-bit counters of the sub-paths (and wavelengths) are lower than 2, and there is wavelength availability on all the sub-paths. In the PR-*Q* algorithm, a connection is set up allocating an available regenerator on all the intermediate nodes equipped with regenerators forming the path. When a lightpath is selected and it is blocked, the corresponding two-bit counters of the sub-paths causing the blocking (that is, not accomplishing the minimum *Q*-factor threshold) are increased; otherwise, if the connection can be established, the two-bit counters are decreased.

3.3 Network control in case of uncertainty on the physical-layer parameters

The main focus of this work is to study the behavior of the control algorithms when the network is operated under uncertainty on the physical-layer parameters.

In order to simulate uncertainty, we developed an ad-hoc dynamic-traffic network simulator. In particular, the process of connection setup has been implemented in the following way. Upon a connection request, first the network control system computes the RWA for the lightpath using one of the two algorithms presented in Sections 3.1 and 3.2. If the lightpath allocation is feasible, then an attempt is made to set it up according to the computed RWA. Since the values of the physical-layer parameters that the control system has used in the RWA computation may now deviate from the real values, there is no guarantee that the lightpath can be actually setup according the computed RWA. We have assumed that if the computed RWA is unfeasible because the signal degradation is more than foreseen, then the connection is blocked forever (there is no RWA recalculation by the control system).

In the above context, the following definitions are given:

- Q_{p_RWA} is the Q factor of a lightpath or a sub-path **p** computed by the control plane at the end of the RWA procedure using the set of values of physical-layer parameters known by the control plane itself. By definition, $Q_{p\_RWA} \geq Q_{min}$ for the sub-paths;
- Q_{p}_act is the real Q factor, computed with the actual set of physical-layer parameters, which may not match the values used by the control plane to compute Q_{p_RWA}. If $Q_{p}\_act < Q_{min}$ for any sub-path of the connection, then the connection is blocked.

In ideal conditions (Perfect Knowledge Perfect Matching – **PKPM**), there is no uncertainty, hence if Q_p is the value of Q that path **p** would have in the designed network: $Q_p = Q_{p\_RWA} = Q_{p}\_act$. In such situation the physical layer behaves as predicted in the design phase and the control plane is able to exactly measure impairments.

When uncertainty on the physical-layer parameters is assumed, then the Q factor evaluated in the design phase (Q_p) and/or Q_{p_RWA} evaluated by the control plane starts deviating from Q_{p}_act. Obviously, the interesting cases are those in which the design procedure and/or the control plane *overestimate Q*.

We had to face the problem of how to reproduce such deviations in our simulations, as there are multiple ways in which estimations can be inaccurate. For example, one could create random deviations evenly distributed in the whole network, or concentrated only in few transmission systems, or else could generate deviations concerning all or just a subset of impairments, etc. We have chosen a very simple approach: we have assumed that all mis-estimations (no matter in which link they are generated and to which effect they are due) combine together producing a fixed overestimation X on the calculated values of Q. More precisely, we have reproduced the following two uncertainty scenarios:

- **Perfect Knowledge Imperfect Matching** (**PKIM**): $Q_{p\_RWA} = Q\_act$ for all the sub-paths setup for the dynamic connection requests, but $Q_{p}\_act = Q_p - X$ [dB]. In this case the design procedure has been too optimistic: all the transmission equipment behaves worse than expected. The combined effects of the worsened performance result in the X degradation factor that measures the mismatching between design and reality. Still uncertainty does not affect routing directly: the control plane automatically adapts to the unpredicted situation because impairments are perfectly measured during RWA calculation for the connections. However, in PKIM uncertainty indirectly affects the network performance (in terms of blocking probability) because less resources and regenerators have been deployed compared to the PKPM case.
- **Imperfect Knowledge Imperfect Matching** (**IKIM**): $Q_{p\_RWA} = Q_{p}\_act - X$ [dB] for all the sub-paths setup for the dynamic connection requests; fur-

thermore, $Q_{p\_}act = Q_p - X$ [dB]. To the overestimations in the design phase, in IKIM we add control-plane overestimations. There is the possibility that $Q_{p\_}act$ falls below the threshold value for some sub-path, despite $Q_{p\_RWA} \geq Q_{min}$ for all sub-paths. Thus, some connections that were thought to be feasible are actually blocked when their setup is attempted, after their feasibility is checked with the real physical layer parameter.

This approach of creating mismatching by a fixed amount of decibels of degradation on each sub-path is simple but effective in producing a degradation of network blocking performance. It should be noted that, although not considered in this study, also sub-estimation of the Q factor is interesting, at least in the case of imperfect matching. Q-factor sub-estimation would not lead to unexpected performance degradation, but rather to unnecessary CAPEX. Extra-expenditure due to sub-estimations will be compared to the loss of revenues (higher number of blocked connections) due to over-estimations in a future development of this work.

4 Simulation results

In this case study, transparent network planning is followed by a set of simulation sessions performed with both *predictive* and *deterministic* algorithms. The aim of the whole set of dimensioning and simulation sessions is to evaluate the behaviour of the two algorithms and in particular to evaluate the advantage of the *predictive* algorithms to face the uncertainties in the network parameters or imperfect matching of the design and operational conditions.

The network used in this study is the Pan European network with 28 nodes and 41 links (see Figure 3) reported in Deliverable D2.1 of the European project NOBEL 2 [16]. All links are equipped with systems of $W = 40$ wavelengths each, each WDM channel modulated at 10 Gbit/s (assuming an optical bandwidth per channel of 0.1 nm). The number of systems installed in parallel on each link is calculated by the design procedure.

Static traffic is defined by a uniform matrix of demands including one bidirectional request for a 10 Gbit/s connection between each pair of nodes (i.e. 378 bidirectional connections in total).

The set of values of the input parameters used to model the physical layer (according to Section 2.2) is reported in Table 1. The table refers to the PKPM case. The values appearing in the table have been proposed and adopted in studies developed within the European project NOBEL 1 [15]. They have been obtained by experimental measurements carried out on commercially-available DWDM transmission systems.

Results of the dimensioning phase in terms of total number of installed regenerators and installed 40 lambda systems are reported in Table 2, for three different values of Q_{min}. $Q_{min} = 17$ dB roughly corresponds to a BER of 10^{-12} (assuming no forward error correction is performed). The table shows that the number of systems does not depend on Q_{min}, while the number of regenerators needed decreases with Q_{min}.

Fig. 3. Pan European Network used in the study.

Table 1 - Physical model parameters

s - max span length [km]	85
α - cable attenuation [db/km]	0.23
QN - quantum noise	58
NF - EDFA noise figure (booster and line amplifiers) [dB]	5
P_0 - [dBm] - Source Power	3
TN [dB] - Node attenuation in dB	13.0
a_0 - first coefficient, Eq. 1	0.4
a_1 - second coefficient, Eq.1	0.96
a_2 - third coefficient, Eq.1	-0.041
a_3 - fourth coefficient, Eq.1	0.02
B - power, Eq. 1	0.2

Table 2. Regenerators and system required for different values of Q_{min}.

Q_{min}	Installed Regenerators	Required full line systems (40 λ each)
17 dB	219	56
16 dB	165	56
15 dB	129	56

Let us now present the dynamic-traffic simulation results. We recall that the network has been previously dimensioned on the basis of a uniform static matrix. In order to have a good topological matching between dynamic traffic and network capacity a uniform dynamic traffic has been generated as well. Different average load values between each node-pair in the network have been tested, from 0.1 to 1 Erlang. All dynamic simulations are performed with $Q_{min} = 15$ dB, i.e. with the lowest number of regenerators installed.

An overestimation factor $X = 2$ dB has been introduced both for the imperfect matching and for imperfect knowledge. The objective of the simulations is the evaluation of the blocking probability in different conditions for the two RWA algorithms presented in Section 3. Fig. **4. Blocking probability for the two algorithms** shows the blocking probability as a function of load obtained by simulating the two RWA algorithms in the three uncertainty conditions PKPM, PKIM, IKIM. We observe that the *deterministic* algorithm performs better in case of perfect knowledge, regardless of the matching condition (only under high traffic load a little worsening in performance is observed in case of imperfect matching). This is expected: the *deterministic* algorithm can route each connection on the base of available resources without mistakes in *Q*-factor computation. Under IK conditions, the *deterministic* algorithm suffers of systematic *Q*-factor overestimation over a set of routes. This is the reason of the flat profile of blocking probability as a function of load for the IKIM case: independently of the load the same routes are blocked due to the inaccuracy in *Q*; the percentage of blocking equals the percentage of routes on which *Q* is systematically overestimated. The *predictive* algorithm performs better only in case of imperfect knowledge and demonstrates its robustness to cope with the uncertainty on physical-layer parameters. The reason for this is that, thanks to its ability to learn from past mistakes and successes, the *predictive* algorithm can avoid systematic blocking events.

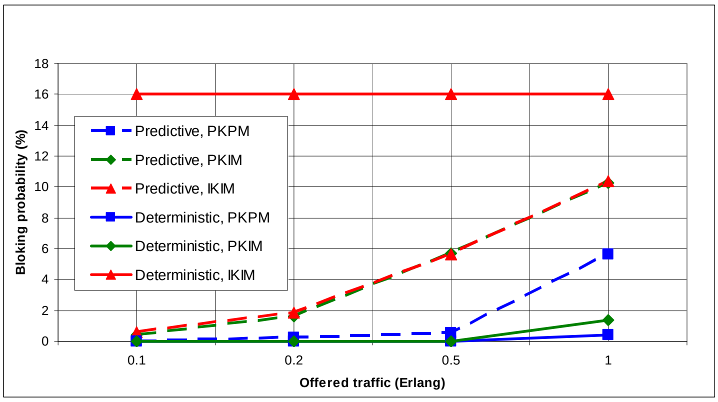

Fig. 4. Blocking probability for the two algorithms

5 Conclusions

In this chapter we have compared *deterministic* and *predictive* RWA algorithms on semi-transparent networks in order to evaluate their robustness under uncertainty on the values of the parameters of the physical layer. After a planning/dimensioning phase, we have simulated a semi-transparent network in dynamic-traffic conditions. In the dimensioning phase network resources and regenerators can be dimensioned correctly or by overestimating signal quality when **imperfect matching** occurs between assumed and real physical-layer parameter values. In the dynamic-traffic phase, the control plane can compute RWA according to reality or again overestimating signal quality when **imperfect knowledge** of the physical layer occurs.

The main outcome of this study is the evidence that, at least in the cases tested, a *deterministic* RWA approach is able to benefit from the availability of detailed physical-layer information as long as this is accurate. In such conditions the *predictive* approach is not useful. When inaccuracy increases, however, the *deterministic* algorithm starts loosing its effectiveness, while *predictive* routing reveals its robustness. For the highest uncertainty, when imperfect matching combines with imperfect knowledge, prediction routing becomes significantly better than the *deterministic* one. In the scenario of simultaneous imperfect matching and imperfect knowledge, realistic if we consider a degradation factor X of 2 dB, the gain in blocking probability we get from prediction ranges from 40% for 1 Erlang traffic to over 90% for low traffic loads.

A practical guideline message could be drawn with potential interest for optical-network operators, control-plane developers, and researchers working on new standard preparation. The best approach to adopt when routing connections in a semi-transparent network depends on the level of accuracy of the characterization of the physical layer and of the transmission impairments. If information is guaranteed to be very accurate and there is an actual correspondence between nominal and real parameters, then a *deterministic* routing approach is the best choice. Otherwise, it is better to rely upon a routing algorithm which ignores the exact physical layer at the beginning, allowing it to be discovered during network operation, learning form the success or failure of the connection setup attempts.

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