Constraint-based path selection methods for on-demand provisioning in WDM networks

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Abstract-- **We propose a framework for decentralized path selection and on-demand wavelength channel provisioning in WDM networks with routing constraints. Within this framework, the path information of choice, such as transmission quality, reliability, policy and traffic conditions, is updated following a connection request, based on a local, autonomous and service-differentiated characterization of optical network elements. It is this local and autonomous network state information that makes our approach particularly suitable for distributed implementation, and applicable to optical network architectures and control protocols that support service level guarantees. To illustrate this, we study mesh networks consisting of transparent, short-reach networking segments interconnected by long-reach WDM links with electronically regenerative gateways, where different link types show different SNR degradation, reliability and delay. On the example of electronically regenerative gateways, we address a new class of constraint-based path selection problems, where a certain a type of network element can at the same time deteriorate and improve network performance; e.g. electronic regenerators improve optical path quality and can adapt to wavelengths, but induce delays or operational costs. The performance study has shown the capability of our methods to accommodate arbitrary number and type of optical path properties, related to different network architectures and services.**

A. INTRODUCTION

The recent emerging of high bit-rate IP network applications is creating the need for on-demand provisioning of wavelength-routed channels with service-differentiated offerings within the transport layer. To fulfill these requirements, different optical transport network architectures have been proposed, driven by fundamental advances in WDM optical technologies. The availability of ultra long-reach transport and all-optical switching has enabled the deployment of *all-optical networks*. However, due to the lack of all-optical signal regeneration, accurate engineering of analogue WDM spans becomes critical. With dynamic wavelength routing, different paths are likely to show different performance in terms of transmission quality due to the additive nature of signal degradations, making the provisioning of on-demand wavelength channels in all-optical (transparent) networks a challenging task.

On the other hand, optical network architectures that include electronic regeneration at each switching node (referred to as *opaque optical networks*) resolve the problem of traffic impairments but impose different sets of limitations to the wavelength-routed channels. In fact, although electronic regeneration simplifies the WDM span design and resolves wavelength continuity constraints, it also adds delay, can significantly reduce the connection (and network) reliability and increase operational costs. For these and other optical transport network architectures, as well as for multi-vendor environments, the availability of routing information for efficient protocols will be critical to enable dynamic and service-differentiated wavelength provisioning. Moreover, to ensure common control platforms with the higher layer networks control (as discussed in context of GMPLS [1]), new approaches to path-selection computation among the intermediate nodes between source and destination are needed.

In this paper, we propose a generic approach to a decentralized, on-demand provisioning in fully or partially electronically regenerative, constraint-based routed, multi-service WDM networks. More precisely, we try to solve the multi-constraint, QoS-routing problem based on the availability of a local rather than global network state information, which we believe to be the first attempt to control the amount, type and distribution of wavelength routing information in a decentralized fashion. Furthermore, we address a new class of constraint-based path selection problems, namely those considering network elements which at the same time deteriorate and improve performance; e.g. electronic regeneration improves the transmission quality of optical paths, but it may induce delays or higher operational costs. In previous research on constraint-based wavelength routing the use of el. regeneration has been shown difficult to resolve with standard graph-theoretical methods, owing to the negative weights, which are necessary if improvement in transmission impairments is the optimization objective [2, 3]. The method presented here overcomes these problems due to its property of concurrent handling of arbitrary number and type of routing metrics, of which the correctness depends only on network elements locally. We have simulated ring, mesh-torus and full-mesh WDM networks consisting of transparent, short-reach networking segments interconnected by long-reach WDM links with electronically regenerative gateways, where different link types (e.g. short-reach, long-reach) show different SNR degradation, reliability and delay. We show that decentralized QoS-based wavelength routing is of particular importance in the case of multi-service networks, where the need for service-differentiated attributes may significantly affect the amount, type, and state of routing information.

B. NETWORK MODEL

The method presented here relies on autonomous and service-differentiated characterization of optical network elements [2]. We use the term network element (NE) in a broader sense: it stands for any *autonomously manageable* physical resource or a group of physical resources along wavelength-routed paths (e.g. fiber amplifiers, regenerators, nodes, etc.) that might affect the wavelength channel performance associated with a certain optical network service. We particularly concentrate on the locally maintained network state information, which

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would enable a simple and robust path selection in arbitrary network architectures, such as all-optical as well as fully or partially electronically regenerative. This local network state information is related to the attributes of optical paths, an example of which may be transmission quality, reliability, routing policy and traffic conditions. Based on this local network state information *a choice* among different feasible paths is made at destination, according to service-level agreements and optical network operational objectives.

1st. Local network state information

We model WDM network as a graph $G(V,E)$, with a set of vertices V, corresponding to the number of nodes N, and unidirectional edges E, corresponding to the set of WDM links L, where for every v_i, $v_j \in V$, there is maximally one directed edge between v_i and v_j, so that $(v_i, v_j) \in L$. For this network, a pool of wavelengths per link $\Lambda=\{\lambda_1,\lambda_2, ...,\lambda_F\}$, and an optical network service set $S=\{S_1,S_2,...S_P\}$ is defined[1]. We consider the total number of network elements H, where $H := \sum^{N,L}\sum^{T} h_k$, $k=1,2...T$, h_k referring to type k of a network element (NE) within a node N or link L from G. For simplicity, a network element associated with a node or link from G is denoted as $h_k^{N,L}$, $k=1,2,...T$, for example $h_1^{N_1}$ being transmitter (Tx) at N_1, $h_1^{N_2}$ being Tx at N_2, $h_2^{N_2}$ being receiver (Rx) at N_2, $h_5^{L_2}$ being fiber amplifier at L_2, etc. Upon a request for a wavelength-routed connection, all NEs relevant to the requested service type, up to $LT+NT$ totally, will be considered. For the purposes of path selection, each NE is characterized by the so-called *Service-specific Wavelength Set* (SWS) and *Local Network State Information*, $\bar{\boldsymbol{a}}$.

Definition 1. *Service-specific Wavelength Set (SWS)*

For each network element $h_k^{N,L}$, $k=1,2,..T$, we define a *Service-Specific Wavelength Set*, $\Lambda_{SWS}[S_r, h_k^{N,L}] \subseteq \Lambda$, such that by allocating a wavelength $\lambda_m \in \Lambda_{SWS}$ on that network element, the on-demand (requested) optical network service $S_r \in S$, $r=1,2,..P$, can be provisioned with sufficient quality in terms of service-level agreements.

The above definition assures that for a demanded service, the wavelength routing will consider only the wavelengths from the corresponding Λ_{SWS} on a certain NE. For example, if service S_1 is demanded and Λ_{SWS} of that service at the network element "Transmitter (Tx)" is $\Lambda_{SWS}[S_1,Tx]=\{\lambda_6, \lambda_7\}$, for accommodation of services S_1 with quality guarantees, only these two wavelengths are considered for wavelength routing at Tx. This rule obviously holds even if the tuneable range of this transmitter included more wavelengths, e.g. $\{\lambda_1, \lambda_2, ...\lambda_8\}$; here, other available wavelengths may be either better suitable or pre-reserved for other service types offered in this network. Note that for wavelength continuous network elements, the choice of wavelengths to be allocated may be further constraint to compatible wavelengths on the incoming and outgoing links of that network element.

Definition 2. *Local Network State Information*

For each network element $h_k^{N,L}$, $k=1,2,..T$, relevant to the performance of the on-demand service $S_r \in S$, $r=1,2,..P$, there exists a local network state information represented as $\bar{a}[h_k^{N,L}, S_r, \lambda_i]$, if and only if $\lambda_i \in \Lambda_{SWS}[S_r, h_k^{N,L}]$.

The local network state information $\bar{a}$ generally assigns several components (metrics) related to the network element $h_k^{N,L}$ and wavelength λ_i. For example, for a certain service type, e.g. S_1, the wavelength λ_3 can be 'idle' or 'busy', being an example of scalar local routing information. Generally, however, $\bar{a}$ will be a vector of values. The candidate components of the vector $\bar{a}$ can be divided into two groups: those that change with traffic conditions and the others, invariant with this respect.

2nd. Path information

The purpose of components building the vector of local network state information is to obtain a methodology for comparing the properties of various paths, with the ultimate scope of efficient routing and resource allocation. For comparison of multi-dimensional metrics put on paths, we refer to the notion of lattices [4]. The lattices can be explained by the so-called ordering, denoted as $\preceq$, being a special relation on an arbitrary parameter set A, with an operator of path optimization, having the properties of reflexivity, anti-symmetry and transitivity. For illustration of a lattice with two-dimensional vectors refer to Hasse diagrams discussed in [4].

For operation with multidimensional properties of $\bar{a}$, we will use the operator °, i.e.

$$\circ : a' \in \Re^i, a'' \in \Re^i \rightarrow a' \circ a'' \in \Re^i \ .$$

A comparison with $\preceq$ between two vectors of local network state information can be then defined as

$$\begin{pmatrix} a_1' \\ a_2' \\ .. \\ a_n' \end{pmatrix} \preceq \begin{pmatrix} a_1'' \\ a_2'' \\ .. \\ a_n'' \end{pmatrix} \Leftrightarrow a_1' \le a_1'' \wedge a_2' \le a_2'' \wedge .. \wedge a_n' \le a_n'' \qquad (1)$$

According to the properties of the quality attributes included into the definition of the properties of $\bar{A}$, the operator of path optimization can be additive (sum), multiplicative (product) or restrictive (minimum value), for which the optimization objective can be minimization or maximization of the component of path information [5]. For example, "maximum SNR path" or "most reliable path" objectives need maximization, while

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[1] We keep to the definition of optical network service to be the set-up of optical paths for different optical network clients, e.g. SDH or IP, such that the *optical* QoS is guaranteed [3]. The optical service-level guarantee is achieved by appropriate allocation of particular wavelengths on concatenated physical resources, i.e. from transmitters via fibers and nodes to receivers, by which service-differentiated requirements on transmission quality, restorability, policy, etc. are taken into account.

"minimum number of hops" or "minimum SNR degradation" needs minimization.

For the further presentation of the model, the following definitions will be useful.

Definition 3. *Path information*

The path information, $\bar{a}(P_{sd}^{Sr})$ is a generic function of the sequence of the states of network elements $h_k^{N,L}$, k=*1,2,..T* each characterized locally and specifically to the service $S_r \in S$, *r*=1,2,..*P*, along the path P_{sd} defined as a sequence of vertices $v_s, \ldots v_i, v_{i+1}, \ldots v_d$, such as $\forall v_i \in P_{sd}$, $(v_i, v_{i+1}) \in E$, i.e.

$$\bar{a}(P_{sd}^{Sr}) = \bar{a}(h_i^{v_s,v_{s+1}}) \circ \ldots \circ \bar{a}(h_j^{v_i,v_{i+1}}) \circ \ldots \circ \bar{a}(h_k^{v_{d-1},v_d}) \qquad (2)$$
$$1 < i < T, 1 < j < T, 1 < k < T.$$

For simplicity, we skipped service-differentiated notation of the compound function of the local network state information and assumed that this is automatically included according to Definition 2.

Definition 4. *Optimal path*

The path $P_{sd}^{Sr,opt}$ is optimal if for any path $P_{sd} \in P$, between source and destination, *P* being set of all paths, and service $S_r \in S$, *r=1,2,..P* , is

$$\forall P_{sd}^{Sr} \in P := \bar{a}(P_{sd}^{Sr,opt}) \preceq \bar{a}(P_{sd}^{Sr,i}), \qquad (3)$$

according to the definition of $\preceq$. (Note that any other definition of the operator denoted by $\preceq$, i.e. different from (1), can be made.)

Definition 5. *Feasible path*

For each on-demand service $S_r \in S$, *r=1,2,..P,* the feasible path is the path that satisfies bounded requirements $\bar{d}(S_r)$ put on that path for each component of $\bar{a}(P_{sd}^{Sr})$.

For example, if a path has to fulfill two different requirements, e.g. transmission degradation being upper bounded by D and reliability lower bounded by R, it is said to be feasible, if the values of network states related to this path a_d and a_r are within these bounds, i.e.

$$\bar{a}(P_{sd}) = \begin{pmatrix} a_d \\ a_r \end{pmatrix}, \bar{d}(S_r) = \begin{pmatrix} D \\ R \end{pmatrix}$$
$$\bar{a}(P_{sd}) \preceq \bar{d}(S_r) \Rightarrow a_d < D, a_r > R.$$

3rd. Solving routing problem

Let us assume a network $G(V,E)$, for which the edges $(v_i, v_j) \in E$ are characterized by two different properties $\bar{a} = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$. For simplicity and without loss of generality, only edges (links) are used as network elements and only two different properties are taken per edge, but any other number of properties or type of network elements can be easily taken into consideration. For example, it is valid to combine the properties of a network element with the same type of properties of its incoming link. (We will see later on, however, that the mixed-type quality metrics cannot be generally used.)

For any path P_{sd} defined as a sequence of vertices $v_s, \ldots v_i, v_{i+1}, \ldots v_d$, $v_i \in P_{sd}$, $(v_i, v_{i+1}) \in E$, let us consider the path information $\bar{a}(P_{sd})$, as defined by (2).

Given any source-destination pair of nodes within the graph G, and the constraints on the routing and wavelength allocation of requested service $\bar{d}(S_r) = \begin{pmatrix} d_1 \\ d_2 \end{pmatrix}$ put on the vector of components a_1 and a_2, correspondingly, the *multi-constrained routing problem* can be defined as follows:

> *Find a path between source and destination that satisfies bounded requirements for each component of the path information.*

The path found according to the above request is *feasible,* as defined by Definition 5. Note that the constraints put on path selection are derived from the service-level agreements of the requested service for which a path P_{sd} has to be provisioned. Also here, the explicit service-related notation is skipped for simplicity.

We will now prove that if an optimum path exists, it is member of the set of feasible paths we select from.

Lemma 1. For each feasible path P_{sd} and the vector of constraint put on that path $\bar{d}(S_r)$, i.e. $\bar{a}(P_{sd}{}^{i}) \preceq \bar{d}(S_r), \forall P_{sd}$, if $\exists P_{sd}{}^{opt}$ then $P_{sd}{}^{opt} \in P_{sd}$.

Proof. Assume that $\bar{d}(S_r) \prec \bar{a}(P_{sd}{}^{opt})$. For the most general operator $\preceq$ of a two-fold metric and a path associated with the path information, i.e.

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \preceq \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} \Leftrightarrow x_1 \le y_1 \wedge x_2 \ge y_2 \,,\ \bar{a}(P_{sd}) = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix},$$

it is valid that $d_1 \ge a_1$ and $d_2 \le a_2$.

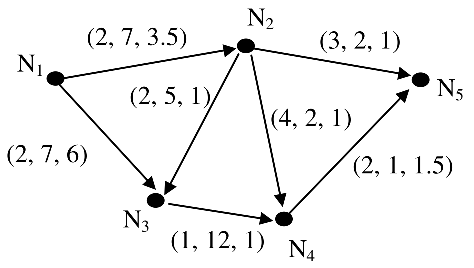
The defined operator and the statement $\bar{d}(S_r) \prec \bar{a}(P_{sd}{}^{opt})$ implies $d_1 < a_{1\mathrm{opt}}$ and $d_2 > a_{2\mathrm{opt}}$. This implies that $a_1 < a_{1\mathrm{opt}}$ and $a_2 > a_{2\mathrm{opt}}$, i.e. $\bar{a}(P_{sd}) \prec \bar{a}(P_{sd}{}^{opt})$, which is in contradiction with Definition 4. (Herewith, we have also proven the transitivity property of the operator $\preceq$.)

Let us illustrate the above network model on the network example given in Figure 1. Here, the link state information contains SNR-degradation, number of free wavelengths and (monetary) cost. For simplicity, we combined the states of network nodes and corresponding network elements into the link states and assumed full wavelength shifting and wavelength independent SNR degradation. Considered is a requirement on path quality between the nodes N_1 and N_4 to be the min. transmission degradation (q), max. number of residual wavelengths (w), and min. operational costs (c). The comparison $\preceq$ and the operator $\circ$ for q, w and c of $\overline{a}(P_{sd})$ are defined in Table 1. The network states are given as three-dimensional vectors of values, each vector component representing the corresponding path information attribute. According to Table 1, the shortest path candidate has the following path information:

$$\overline{a}(P_1) = \overline{a}(N_1, N_2) \circ \overline{a}(N_2, N_4) = \begin{pmatrix} 2+4 \\ \min(7,2) \\ 3.5+1 \end{pmatrix}.$$

The solution space obtained by searching the optimal path between the nodes N_1 and N_4 contains the paths

$$P_1(N_1,N_2,N_4) = \begin{pmatrix} 6 \\ 2 \\ 4.5 \end{pmatrix}, P_2(N_1,N_3,N_4) = \begin{pmatrix} 3 \\ 7 \\ 7 \end{pmatrix}, P_3(N_1,N_2,N_3,N_4) = \begin{pmatrix} 5 \\ 5 \\ 5.5 \end{pmatrix}.$$



Link state = (SNR-degradation, free wavelengths, opeational cost)

FIGURE 1 An example network with link states.

Attribute	Transmission degradation, q Number of residual wavelengths, w Operational cost, c
Network state information	$\overline{a} : A \rightarrow \Re \times \Re$
Operator	$\begin{pmatrix} q_1 \\ w_1 \\ c_1 \end{pmatrix} \circ \begin{pmatrix} q_2 \\ w_2 \\ c_2 \end{pmatrix} = \begin{pmatrix} q_1 + q_2 \\ w_1 \min w_2 \\ c_1 + c_2 \end{pmatrix}$
Comparison	$\overline{a}_1 \preceq \overline{a}_2$: $(q_1 \le q_2) \wedge (w_1 \ge w_2) \wedge (c_1 \le c_2)$
Path Information	$\overline{a}(P_{sd}) = \overline{a}(v_s, v_{s+1}) \circ \ldots \circ a(v_{d-1}, v_d) =$ $= \begin{pmatrix} \sum_s^d q_k \\ \min w_k \\ \sum_s^d c_k \end{pmatrix}$

TABLE 1. An example of path information.

For illustration, let us assume that the feasible paths are found based on optimization of transmission degradation (q) and number of residual wavelengths (w) only, i.e. the number of constraints is smaller than the number of attributes. By analyzing the solution space of feasible paths, no path rather than P_2 can be found with better transmission quality (minimum degradation) and more free residual wavelengths. Hence, the route P_2 is optimal since it presents the local minima in the solution space[2]. Given a solution space, it is now easy to start considering the more particular constraints. For example, if a connection with maximum transmission degradation being 5 and minimum number of residual wavelength being 4 is acceptable, both paths P_2 and P_3 are feasible. On the other hand, if wavelength continuity has to be kept, feasible paths may not exist subject to wavelength occupancy.

4th. Multi-constraint routing problem revisited

It is known that the problem of finding a path subject to multiple constraints is inherently hard. Generally, the problem of finding a path subject to constraints on two or more additive and multiplicative metrics in any possible combination is NP-complete [5, 6]. For example, finding a feasible path for two additive constraints (e.g. delay and cost) is known to be NP-complete. Some general approximation schemes that are ε-optimal have been proposed, being of polynomial complexity but computationally prohibitive [7].

In a multi-service network, the issues of performance optimization under multiple constraints get even more complicated. For a multi-service network scenario, it is hard to determine the best network operating point for different types of traffic. On one hand, service-differentiated traffic should not be affected due to the resource reservation, while on the other hand, the overall network operation and performance should not degrade. In addition, the maintenance of the network state information plays an important role, particularly in the highly dynamic network environments with excessive load fluctuations.

In [2], we have studied multi-constrained routing problems for finding the path, which satisfies users' requirements under network constraints put on multiple measures. In that approach, we have searched for the candidate paths with a precedent metric first, by eliminating the edges with a restrictive constraint from the so-called transformed network graph. Then we have shown that a two-constraint problem can be solved, with a complexity of the shortest path algorithm applied. We found out however, that for different network elements and states, which may be summed or multiplied along the path, it is difficult to define the *relative size* of network state descriptors needed in a centralized network representation with graphs. For example, the (mixed) cost of a link with high reliability, but low SNR is difficult to define.

As previously stated, this effect exacerbates the applicability for networks with electronically regenerative optical paths, due to the "negative weights" when transmission degradation is one of the routing criteria. Our previous work [2] has for the first time presented the study of the impact of electronic regeneration on constraint-based path selection by taking into

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[2] Note there might be paths $P_{sd}^{\ 1}$ and $P_{sd}^{\ 2}$, where $q(P_{sd}^{\ 1}) < q(P_{sd}^{\ 2})$, but $w(P_{sd}^{\ 1}) > w(P_{sd}^{\ 2})$, which means that one route offers better transmission quality, but less residual wavelengths. For routing purposes, such scenarios are of particular interest [4].

account the transmission quality and blocking probability[3]; we have however identified the difficulties with methods of path algebra. With electronically regenerative optical paths, if the shortest path represents the least degradation, the negative weights are needed in the graph-theoretical representation of electronic regeneration, for which the standard two-constraint QoS-methods based on shortest paths cannot be applied. Moreover, even if negative weights were tractable, their size and usage are difficult to estimate for dynamic routing given a variable path length of which the transmission degradation has to be compensated. For example, if SNR degradation is weighted 3 (dB) per hop and the overall SNR degradation cannot exceed 12 (dB), the all-optical paths up to 4 hops are valid. After two hops, regeneration may compensate for 6 (dB) degradation originating from the traversed paths, after 3 hops for 9 (dB), etc. This effect cannot be dimensioned in a centralized representation of the network states for dynamic routing, e.g. based on graphs [2].

In this work, by introducing a distributed-like, decentralized method for path selection, link weighting is avoided, as well as relative size of weights describing multiple quality attributes (e.g. reliability, delay or transmission quality). In fact, for a distributed-like wavelength channel provisioning, we have adopted the method from [8, 9, 10], where a distributed method to QoS-routing based on *probing* messages has been presented. Also here, a choice of the best path is made at destination, according to the network properties, traffic conditions or types of services. The *wavelength probe* messages related to a certain path are flooded, similarly as in [9]. The messages are forwarded when a neighbor of the affected node was not visited, or discarded otherwise; the record of the visited nodes is contained within the message and assures a loop-free operation.

Flooding is the principle which generally requires the consideration of scalability for large number of the network elements. Intrinsically, the flooding-based distributed algorithms do not require any global state to be maintained and the routing can be done entirely based on local states [9, 10]. Yet, most of the distributed routing algorithms presented so far assume the existence of distance vectors that correspond to global states, which shares the same problem as centralized routing but can simplify signaling [5, 11]. The accuracy of the global state information might lead to problems with path loops and special approaches to QoS-routing with respect to possibly inaccurate state information may be necessary [12].

In this paper, we also discuss the feasibility of our method according to the number of wavelengths and network size. Unfortunately, we could not compare our strategies with "true" distributed protocols, as we are lacking in the corresponding simulation environment. Therefore, for implementation of our "distributed-like" path selection strategies, we adapted the Bellman-Ford shortest path algorithm for routing and connectivity information update at each node, for all loop-free paths. With an extension of the Bellman-Ford algorithm, it is possible to identify all loop-free paths up to any possible number of hops *n* or up to a certain *cost* limit. This group of paths always includes the shortest path and all paths with comparable properties in terms of *hops* or *cost* respectively. In [8], an adaptation of the Bellman-Ford algorithm is used to compute minimum hop paths that satisfy multiple metric cost bounds. As it will be shown next, we have adopted this principle to deal with multi-objective, constraint-based wavelength channel provisioning.

C. ON-DEMAND PROVISIONING OF WAVELENGTH PATHS

To overcome the fundamental complexity of constrained path selection, we propose a protocol for on-demand wavelength channel provisioning, suitable for distributed implementation, with local, instead of global, network state update under dynamic traffic conditions and multiple-type services [9, 13]. Our algorithm is implemented as an adaptation of the label-correcting shortest path algorithms, which use flooding of the connection set-up messages from source to destination. The messages are updated based on the local network state information at each traversed network element, and converge in a set of feasible paths by discarding invalid paths towards destination.

5th. Basic approach

For illustration, we will focus to three types of network states: additive (*q*, e.g. SNR degradation, delay), multiplicative (*r* e.g. reliability), restrictive (*w,* e.g. residual capacity in wavelengths) [5]. In addition, we will consider such network architecture where only electronic regenerators, if available, are capable of wavelength shifting, but the presented methods can simply handle any other architecture, e.g. opaque architecture with electronic regeneration but without shifting capability, all-optical network deploying all-optical regenerators, all-optical wavelength converters, or any combination of above.

Distributed discovery of wavelength paths (DWP)

Step 1: Get a connection request between (*src, dest*) for a service S_r, with the service-specific vector of routing constraints on paths $\bar{\boldsymbol{d}}(S_r)=[q, d, r, w]$, i.e. max. transmission degradation $q_{max}(S_r)$, max. delay $d_{max}(S_r)$, min. reliability $r_{min}(S_r)$, min. residual capacity $w_{min}(S_r)$. (Note that for a given connection request another type of service would impose other constraints.)

Create a *path information message* composed from the request, the initial values of $\bar{\boldsymbol{a}}[a_q, a_d, a_r, a_w]$ (e.g. [a_q=0, a_d=0, a_r=1, a_w=*max. number of wavelengths*]) and an initial *path sequence p={id(src)/* Λ_{SWS}*}*. In addition to $\bar{\boldsymbol{a}}$, $\bar{\boldsymbol{d}}$, *src* and *dest*, the path message needs to contain a unique path identifier (*id*) and information regarding the allocated wavelength together with the unique identifiers of the visited network elements, stored as *path sequence p,* to assure loop free operation. Send this message from *src* to all neighboring NEs.

Step 2: Forward the received path information message with updated values of *p* to all neighbors, excluding those which are contained in the *path sequence* ("visited"), until *dest* is reached, according to the following rule.

Path information update

For each idle wavelength from Λ_{SWS}, a visited NE_k updates the values of the path information $\bar{\boldsymbol{a}}[a_q, a_d, a_r, a_w]$, so that a_q and a_d are summed along the precedent NEs, a_r is multiplied,

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[3] Note that also [12] has presented a remarkable study of selective electronic regeneration form the point of view of wavelength shifting: however this method is difficult to extend to a multi-constraint path selection.

while a_w of the considered path is the minimal value, i.e. $\boldsymbol{a}(p_{id})_{new} = \boldsymbol{a}(p_{id}) \circ \boldsymbol{a}(NE_i)$,

for every $\lambda \in \Lambda_{SWS}[p_{id}]_{new} = \Lambda_{SWS}[S_r, NE_i]_{idle} \cap \Lambda_{SWS}[p_{id}]$. Generally, for any sequence of network elements NE_k, i.e. NE_1, NE_2,.. NE_{r-1}, NE_r, NE_{r+1}, …, NE_{k-1}, NE_k, we get

$a_q(p_{id}) = \Sigma d(NE_i)$, $a_d(p_{id}) = \Sigma a_d(NE_i)$, $a_r(p_{id}) = \prod a_r(NE_i)$, $a_w(p_{id}) = \min\{a_w(NE_i)\}$, $i=1,2,..k$

i being the sequence of the precedent NEs, for all idle $\lambda \in \{\Lambda_{SWS}[S_r, NE_i]\}$.

(*Wavelength shifting NE*) For each input wavelength which can be shifted into another output wavelength, a separate path information message is required to track the path quality vector $\boldsymbol{a}(P_{sd})$, even if this one remains the same, i.e. independent of choice of wavelength. This is necessary due to the unpredictable path information updated by network elements to be visited later.

Path information messages which are characterized by wavelength occupancy, unacceptable network states with respect to $\overline{d}(S_r)$ or input-output wavelength incompatibility if wavelength shifting is not possible, are discarded immediately after the update process; they are not forwarded to neighboring nodes and do not reach the destination.

If NE_k is not *dest,* the visited network element *id* and the wavelengths for allocation are added to the *path sequence* variable of surviving messages, which then are forwarded to the neighboring nodes which will then perform Step 2 themselves.

Step 3: From the obtained set of all feasible paths $\boldsymbol{P}_{sd} = \{p_{id1}, p_{id2}, ..\}$ for which $\overline{a}(P_{sd}^{\,i}) \preceq \overline{d}(S_r), \forall P_{sd}$, *dest* selects the best path according to one or more chosen criteria: min. hops, min. cost, min. number of traversed NEs of particular type, e.g. wavelength converters, etc. The information available to *dest* contains: path identifier, all traversed network elements with allocated wavelengths, as well as the path performance expressed in form of the path performance vector $\overline{a}(P_{sd})$.

Step 4: From *dest*, send the acknowledgement message back along the selected path to *src*, for the purpose of resource reservation. The connection can then be established.

Obviously, for choice of the path for provision (Step 3), a number of different strategies might exist, according to the network properties, traffic conditions or types of services. The method DWP is simple, since it does not assume any local *a posteriori* record of the data contained in the messages. The messages related to a certain path identifier are either forwarded when a neighbor of the affected node was not visited, or discarded otherwise; the record of the visited nodes is contained within the message and assures a loop-free operation. Unluckily, the above process is based on flooding abundant messages to be evaluated and updated at each node, and it does not scale well. Thus if the number of visited network elements is N, the number of wavelengths λ, then the number of necessary updates grows with $\lambda \sum_{m=2}^{N} (m-1) \frac{(N-2)!}{(N-m)!}$, in a wavelength-continuous full-mesh network (e.g. with 8 wavelengths and 4 nodes, the number of updates is 88). For full wavelength conversion capability λ needs to be replaced by λ^N, further increasing the complexity.

Therefore, most of our efforts related to simulations of DWP, concentrated on reducing the above complexity. For example, we limited the number of hops of candidate paths, a property which can be easily measured by DWP. To illustrate this, refer to the example network shown in Figure 1 once more. If for defining candidate paths, the ranking has been made according to the number of hops, and the number of hops was limited to two, we could find two candidate paths P_1 and P_2, for the connection request N_1-N_4. At the same time, for the connection request N_1-N_5, only a single candidate path can be found (i.e. N_1- N_2- N_5).

By reducing the number of candidate paths to a certain number of hops, the number of the message updates is reduced to $\lambda \sum_{m=2}^{k+1} (m-1) \frac{(N-2)!}{(N-m)!}$, where k is the maximum number of hops of the candidate paths, which in any case needs to be ≥ the number of hops of the shortest path. Note that for a network topology with low connectivity (e.g. rings), the reduction of the signaling complexity is not as significant as for a mesh topology. For example, in a full-mesh topology with five nodes, a limitation in number of hops to two, which is valid as in the full mesh the shortest path has always one hop, this limitation reduces the number of possible paths from 16 to 4, while the number of necessary updates for message-parameters (Step 2, DWP) is reduced from 49 to 7 per wavelength-path.

Furthermore, the reduction of the complexity can also be obtained if the method DWP is used for wavelength allocation only. In this case, we apply DWP on statically routed, predefined candidate paths, where only those NEs are visited which belong to these paths. Particularly in case of wavelength-differentiated performance with respect to type of service, the proposed method is efficient and simple to perform wavelength allocation. On the other hand, DWP can return route and wavelengths if applied to the whole network. This however leads to a significant increase of the signaling effort, especially in wavelength-shifted and densely connected networks.

6th. Electronically regenerative wavelength paths

We will now show that the algorithm DWP is particularly suitable for electronically regenerative network architectures. As previously discussed, there are three particular properties of electronic regeneration for which the method DWP particularly suits: selective wavelength shifting, variable path length and limited cascadability due to routing constraints which cannot be easily compensated by regeneration (e.g. delay). These properties have been shown to be difficult to handle by weights in network representation with graphs [2].

Regarding the selective wavelength shifting, as we will show next, the extension of the DWP method presented here (called DWP-R) can easily handle any kind of wavelength shifting capability of an optical network element (e.g. full, selective or no wavelength shifting). This is important to state here, since most of the works on opaque network architecture assume that electronic regeneration provides full wavelength shifting capability. However, if node architecture defines all-optical switching, but electronically regenerative SDH line cards per wavelength at the input or output switch ports, as it is the case with most of the commercially available optical node architectures nowadays, this will not be generally the case, since these line cards do not implement tuneable lasers. On the other hand, electronically switched node architectures may provide full wavelength shifting if an arbitrary input wavelength can be chosen even if the output wavelength is kept fixed. However, most generally and independently of switching technology, the electronically regenerative nodes are not selective: the regeneration is always used, even if not necessary form the point of view of signal quality. Thus opaque architectures do not gain from the benefits of all-optical, transparent operation for which the all-optical networks have been proposed in the first place.

Regarding the variable path length and limited cascadeability, in contrast to all other similar methods previously studied, the method DWP can easily handle a particular property of electronic regeneration, i.e. the simultaneous consideration of antipodal performance impacts caused by a single network element: improvement (e.g. transmission quality) as well as impairment (e.g. delay). As previously stated, this feature is difficult to capture by graph representation with weights.

We will now show a special case of the method DWP (which we call DWP-R). Note that the extension shown here can be easily captured by the native approach DWP, which, for clarity, we have kept separated. We also kept the number of attributes the same for easier understanding. It would have been enough though, to take two additive quality matrices, e.g. delay and transmission degradation, to illustrate the effect of electronic regeneration.

Distributed discovery of el. reg. wavelength paths (DWP-R)

Step 1: Get a connection request between (*src, dest*) for a service S_r, with the service-specific vector of routing constraints on paths $\bar{\boldsymbol{d}}(S_r)=[q, d, r, w]$, i.e. max. transmission degradation $q_{max}(S_r)$, max. delay $d_{max}(S_r)$, min. reliability $r_{min}(S_r)$, min. residual capacity $w_{min}(S_r)$. Create and send *path information message* as in DWP.

Step 2: Forward the received path information message with updated values to all neighbors, excluding those which are contained in the *path sequence* ("visited"), until *dest* is reached, according to the following rule.

Path information update

For each idle wavelength from Λ_{SWS}, a visited NE_k except an electronic regenerator, updates the values of the path information $\bar{\boldsymbol{a}}[a_q, a_d, a_r, a_w]$ as defined in Step 2 of DWP, i.e.
$\boldsymbol{a}(p_{id})_{new} = \boldsymbol{a}(p_{id}) \circ \boldsymbol{a}(NE_i)$, for every
$\lambda \in \Lambda_{SWS}[p_{id}]_{new}=\Lambda_{SWS}[S_r,NE_i]_{idle} \cap \Lambda_{SWS}[p_{id}]$. If an electronic regenerator is visited, the parameter a_q is reset to the initial value (e.g. $a_q=0$) prior to the $\boldsymbol{a}(p_{id})$ update as defined above. Generally, for any sequence of network elements NE_k, i.e. $NE_1, NE_2,.. NE_{r-1}, NE_r, NE_{r+1}, \ldots, NE_{k-1}, NE_k$, which includes an electronic regenerator NE_r, we get
$a_q(p_{id})= \Sigma d(NE_i),\ i= r+1, r+2,\ldots k,$
$a_d(p_{id}) = \Sigma a_d(NE_j),\ a_r(p_{id}) = \prod a_r(NE_j),$
$a_w(p_{id}) = \min\{ a_w(NE_j)\}, j=1,2,..k$
i,j being the sequence of the precedent NEs, *r* being the sequence index of the last traversed regenerator, for all idle $\lambda \in \{\Lambda_{SWS}[S_r,NE_i]\}$.

From here on, DWP-R proceeds as in DWP.

Step 3, Step 4: As in DWP.

For illustration, consider a simple WDM network (ring) with three nodes, three unidirectional links and two wavelengths per link, capable of accommodating two service classes, S_1 and S_2 (Figure 2). Assume that S_1 is required between N_1 and N_3, for which the max. transmission quality degradation (e.g. degradation of SNR) should not exceed 30 dB, i.e. $q_{max}(S_1) \leq 30$. For this service type, we consider the following manageable, S_1-specific NEs: $Tx(N_1)$, $Reg(N_2)$, $Rx\ (N_3)$, nodes and links, with their associated service-specific wavelength sets and quality properties (Table 2). Here, only N_2 can provide wavelength shifting and only for S_1, due to the S_1-specific properties. The network state information is expressed as a pair value $\bar{\boldsymbol{a}}[a_q, a_d]$, corresponding to transmission quality degradation and delay. Note that any restrictive attributes can automatically be taken into account by the definition of Λ_{SWS}; wavelengths outside Λ_{SWS} are simply excluded from the path discovery (e.g. link L_3).

The source S forwards the connection request to its first neighboring network element (here: Tx), by generating two (being number of wavelengths) pieces of path information of type [path identifier, service requirements $\mathbf{d}(S_1)$, destination, actual path information, path sequence {network element – wavelength}], i.e. [*mk*, $\mathbf{d}(S_1)$, $id(N_3)$, (0,0), $\{S(\lambda_1)\}$] and [*av*, $\mathbf{d}(S_1)$, $id(N_3)$, (0,0), $S(\lambda_2)$]. Transmitter Tx forwards the updated messages [*mk*, $\mathbf{d}(S_1)$, $id(N_3)$, (4,1), $\{S(\lambda_1), Tx(\lambda_1)\}$] and [*av*, $\mathbf{d}(S_1)$, $id(N_3)$, (4,1), $\{S(\lambda_2), Tx(\lambda_2)\}$] to its neighbor N_1, which then have to generate four outgoing messages to its neighbors N_2 and N_3. Node N_2, for example, receives the following messages: [*mk,* $\mathbf{d}(S_1)$, $id(N_3)$, (17,3), $\{S(\lambda_1), Tx(\lambda_1), L_1(\lambda_1)\}$] and [*av*, $\mathbf{d}(S_1)$, $id(N_3)$, (19,3), $\{S(\lambda_2), Tx(\lambda_2), L_1(\lambda_2)\}$]. After the regeneration however, since wavelength shifting is possible four messages are sent to N_3, i.e. two updated [*mk*, $\mathbf{d}(S_1)$, $id(N_3)$, (0,14), $\{S(\lambda_1), Tx(\lambda_1), L_1(\lambda_1), N_2(\lambda_1), Reg(\lambda_1)\}$], [*av*, $\mathbf{d}(S_1)$, $id(N_3)$, (0,14), $\{S(\lambda_2), Tx(\lambda_2), L_1(\lambda_2), N_2(\lambda_2), Reg(\lambda_2)\}$], and two newly generated [*mi*, $\mathbf{d}(S_1)$, $id(N_3)$, (0,14), $\{S(\lambda_1), Tx(\lambda_1), L_1(\lambda_1), N_2(\lambda_1), Reg(\lambda_2)\}$], [*sb*, $\mathbf{d}(S_1)$, $id(N_3)$, (0,14), $\{S(\lambda_2), Tx(\lambda_2), L_1(\lambda_2), N_2(\lambda_2), Reg(\lambda_1)\}$]. The two messages *mi* and *sb* are generated as a consequence of wavelength shifting capability of the regenerator at node N_2. The process continues in the same fashion until the destination (D) is reached.

In this example, the destination may chose the best path in terms of transmission quality, i.e. $Tx\text{-}N_1\text{-}L_1\text{-}N_2\text{-}Reg(N_2)\text{-}L_2\text{-}N_3\text{-}Rx$ at λ_1(wavelength continuous), with overall transmission degradation $\Sigma q=10+3+5=18$ (<30). Note that the losses $Tx\text{-}N_1\text{-}L_1$ ($\Sigma q=4+3+10/12$) are compensated by the electronic regeneration at N_2 and do not contribute to the overall path degradation. However, if the request on delay for this service was $d(S_1) \leq 15$ (time units), this path would show unsatisfactory performance ($\Sigma d=17$, "regenerator-bottleneck"). On the other hand, by avoiding regeneration over the same route, an unacceptable degradation, i.e. $\Sigma q=38$, would be obtained. Another path, e.g. Tx-N_1-L_3-N_3-Rx at λ_2, however, would satisfy both bounds (q and d), i.e. $\Sigma q=21$ (still<30) and $\Sigma d=5<15$. Hence, optimizing one single metric to improve cascadability (e.g. via regeneration) is necessary, but not sufficient to find feasible paths. Note that the NE quality attributes and the routing decision completely change, if a service of type S_2 must be set-up.

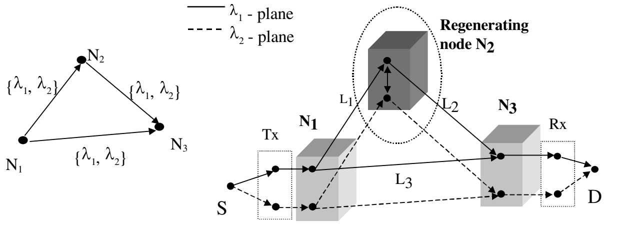

FIGURE 2. An example network with auxiliary representation.

$\bar{a}=\begin{pmatrix} a_q \\ a_d \end{pmatrix}$		a_q [dB]	a_d [time units]
S_1-specific NE			
Tx @N_1	λ_1, λ_2	4	1
Rx @N_3	λ_1, λ_2	5	1
Reg@ N_2	λ_1, λ_2	not applicable	10
N_1, N_2, N_3	λ_1, λ_2	3	1
L_1, L_2	λ_1	10	1
	λ_2	12	1
L_3	λ_1	$\notin \Lambda_{SWS}$: not applic. for S_1 (e.g. insuff. quality)	
	λ_2	6	1

TABLE 2. Example network: S_1-specific network states.

D. PERFORMANCE STUDY

For simulation results, the connection requests arrive according to Poisson process with call holding time being negative exponentially distributed. Traffic distribution as well as distribution of the service requests is uniform; all results are obtained with a confidence level of 95%. For simplicity, we differentiate the service requirements, i.e. different services put different constraints on wavelength paths, but we consider network elements with properties independent of type of service. This is not necessarily a realistic assumption. For example, some network elements may be designed for a particular type of service and therefore will show worse properties to other services or might even be applicable exclusively to that type of service only (e.g. in Figure 2, service S_1 cannot use link L_3, while service S_2 may not be allowed to use the regenerator at node N_2).

As we have previously stated, for implementation of DWP we have not implemented a "true" distributed protocol, as we are lacking in the corresponding simulation environment. Instead, we adapted and extended the Bellman-Ford shortest path algorithm from [8], for routing and connectivity information update at each node. As such, DWP is decentralized as it uses pre-calculated paths and distributed parameters. It exhaustively runs along all paths, until the path messages have either converged toward the destination or were discarded due to service incompatibility or resource occupancy, i.e. no discarding of path messages due to queuing is foreseen. For these reasons, we initially compared DWP with the multi-constrained routing algorithms as in our work [2], where the best path is found after a precedence metric for which then, other quality attributes are checked. However, we became aware of the potential advantage of a multi-path strategy such as DWP with respect to the single-path one, and focused therefore our results on better understanding of the applicability of the DWP to multi-service path provisioning and heterogeneous, selectively regenerative network architectures.

We study three different network topologies: bi-directional ring, full-mesh and mesh-torus. Being less connected, ring networks need less messages which converge faster towards destination, and used them for the results where varying topologies would not significantly vary the performance. To use an upper bound on path length under dynamic traffic conditions, we used the full-mesh network to show the performance improvement yielded by this bound. Finally, the mesh-torus network allows us to better evaluate scalability and impact of wavelength shifting or electronic regeneration. The mesh-torus network has been adopted by many researchers for performance evaluation of all-optical networks [14, 15]. The mesh-torus network can be viewed as an extreme case with respect to the number of hops required in a mesh network.

For all networks studied here, in order to achieve different properties per path, we use three different WDM link types (*Type A, Type B, Type C*). We assumed that the main parameter of the transmission fiber, called "transmission degradation" is defined *per wavelength* i.e. parameter comprising all relevant transmission attributes. At the same time we assumed that reliability and other parameters are the same for all wavelengths; long-reach links are taken less reliable and show more delay (e.g. Type C). The transmission degradation per wavelength is defined as follows: a_q [dB] (*Type A, Type B, Type C),* λ_1(5, 9, 12), λ_2(4.5, 7.6, 9.7), λ_3(3.9, 6, 7.4), λ_4(3.4, 4.7, 5), λ_5(3.4, 4.7, 5), λ_6 (5, 9, 12), λ_7(6.6, 13.3, 19), λ_8 (8.2, 17.6, 26). The reliability is equal for all wavelengths and differs only according to the link type, i.e. a_r [%] (*Type A, Type B, Type C),* (99.9, 98.75, 97.5).

In the first example, we study a 7-node bi-directional ring topology, of which the properties per wavelength and network element are shown in Table 3. The service-differentiated requirements, which we consider routing constraints, are as follows: $S_1[q_{max}<36\text{dB}, r_{min}>98\%, w_{min}\geq 1]$ and $S_2[q_{max}<90\text{dB}, r_{min}>90\%, w_{min}\geq 1]$. As it can be seen from the results, the method DWP, being a multi-path strategy, yields superior results for both services. This is because DWP method yields several feasible paths, out of which the best can be selected (here: min. number of hops), in contrast to the non-DWP methods where the best path, optimized for two quality attributes (here: min-hop and residual capacity), is checked on remaining requirements (transmission degradation, reliability). While for service S_1 the results are as expected due to the fact that for some calls the shortest path found for a single constraint was not feasible with respect to other constraints (e.g. due to the link types *B* and *C*), the results for service S_2 also improved with DWP. In Figure 3, it can be seen that even in a lightly loaded network the multiple paths yielded by DWP reduce the blocking for S_2, where all shortest paths (due to a single routing criteria, here minimum hops) are feasible for all defined constraints.

NE definitions		a_q [dB]	a_r [%]
Tx, Rx	$\lambda_1, .., \lambda_8$	0	100
N_1,.., N_7	$\lambda_1, .., \lambda_8$	3	99.99
$L_1(N_1\text{-}N_2)$, $L_3(N_3\text{-}N_4)$, $L_6(N_6\text{-}N_7)$, $L_7(N_7\text{-}N_1)$	$\lambda_1, .., \lambda_8$	Type A	99.9
$L_2(N_2\text{-}N_3)$, $L_4(N_4\text{-}N_5)$	$\lambda_1, .., \lambda_8$	Type B	98.75
$L_5(N_5\text{-}N_6)$	$\lambda_1, .., \lambda_8$	Type C	97.6

TABLE 3. Seven nodes bidirectional-ring: NE-properties.

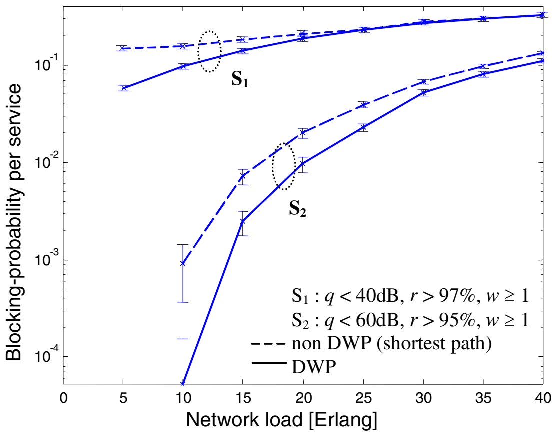

FIGURE 3. Seven nodes bidirectional-ring: blocking probability per service (negative values ignored, busy states included, no wavelength conversion).

We next study the reduction of the convergence time of the algorithm DWP on the example of a seven-node full-mesh network, where a reduced set of pre-routed paths is introduced. To limit the number of candidate feasible paths we define a hop limit that automatically adapts to different connection requests and network loads. Therefore we use a limit relative to the number of hops of the shortest path found, according to a single constraint. For example, if a limit is defined in terms of number of hops and if the shortest path according to a certain constraint is two hops, we include only paths up to three hops (“plus one hop”). The path length limitation as used here reduces the algorithm convergence time, by avoiding messages handling information about paths with hop lengths larger than the limit. Note that the number of hops is an intrinsic variable of the adapted Bellman-Ford algorithm and is therefore advantageous to use, but additionally also a limitation on the used constraints, possibly combined by some cost-function, might be used to further reduce the number of candidate paths.

In this example, we assumed only nodes and links as network elements. All nodes have the same properties per wavelength along the network, [a_q=3dB, a_r= 99.99%]. Transmitters and receivers are modeled as ideal [a_q=0dB, a_r=100%]. Link properties are taken from the previous example; different link types are uniformly and randomly assigned to all neighbors. Due to the full connectivity, compared to the 7-node network from the previous example, this network is analyzed for higher loads. As in all examples, we assume reliability to be constant over time, and compare the proposed algorithm (DWP) with the multi-constraint, single-path (centralized) one. Here, two versions of DWP are used, one which uses a reduced set of feasible paths, where DWP is used for wavelength allocation only, and while the other considers all feasible paths, i.e. where DWP is used for routing and wavelength allocation. Since this exercise aims at measuring the simulation running time, only one single service is considered. The S_1-specific service constraints are as follows: [q_{max}<40dB, r_{min}>97%, w_{min}≥1].

Also here, the distributed, multi-path strategies yield superior results up to the limit where the load is too high and no idle (longer) paths can be found. Note however that already below this limit, the reduction in the number of scanned paths, compared to DWP where all paths are scanned, does not contribute to increased blocking probability. Since longer paths in number of hops are more likely to be occupied, there are only a few feasible paths which are not included in the reduced set. Yet, the reduction in computation time is significant. In fact, the computational effort decreases for higher network loads, as many path information messages are discarded in course of the DWP process. Due to this effect, and, more important, due to the reduction of scanned paths (here: one hop longer than the shortest path), with the reduced set of pre-routed paths, a faster solution for the multi-constrained routing can be achieved (Figure 4).

Finally, we applied the strategy DWP to a large unidirectional mesh-torus network (size: 7×7), with 8 wavelengths per link [12]. For two partially regenerative networks, the optical nodes equipped with electronic regenerators are located diagonally. Two different service classes, S_1 and S_2, are assumed, both with the same requirements on transmission quality (q_{max}<60dB), but different delay constraints: $d_{\max}(S_1)$<100 time units, $d_{\max}(S_2)$<300 time units. For simplicity, we assumed Tx, Rx, and nodes all with same properties per wavelength along the network (nodes [a_q=3dB, a_d=1 time unit]; regenerators [a_q=n.a., a_d =50 time units]); full wavelength shifting is possible only at regenerative nodes and is used only to resolve blocking. Link properties are taken from the previous example: *Type A* for horizontal connections (a_d=2 time units), *Type B* for the vertical ones (a_d=5 time units). Our strategy DWP is used to compare the networks with regenerative and all-optical architectures.

For both services, the usage of regeneration decreases blocking, since both services are limited in optical reach (Figure 5). However, two effects question the role of full electronic regeneration. First, the usage of regeneration in all nodes for services with limited delay (S_1) improves the optical reach, but deteriorates the path QoS properties, and hence increases the blocking. Second, the sparse regenerators (e.g. 7 reg. nodes) can yield comparable results as for full regeneration for some operational ranges (which is in accordance with our results from [2]). Hence, if electronic regeneration cannot be allocated upon necessity but is a fix part of the optical path, and if transmission degradation is not the only routing constraint, the opaque optical network architectures, even if capable of wavelength shifting, will have to deal with other sets of limitations to assure the quality of service.

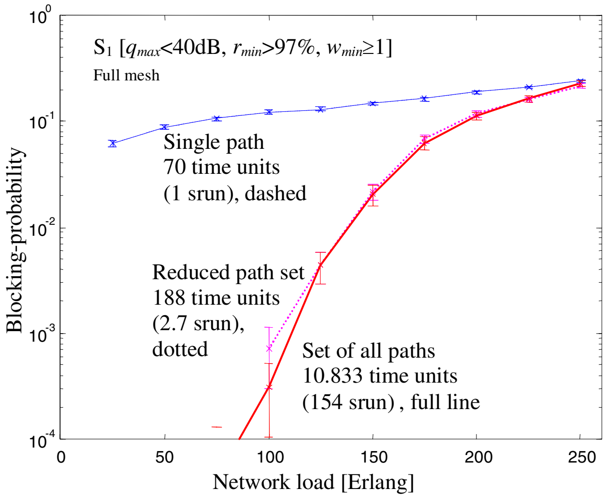

FIGURE 4. Seven-nodes full-mesh network: blocking probability with reduced set and vs. full set of candidate paths (neg. values ignored, busy states incl., no wavelength shifting).

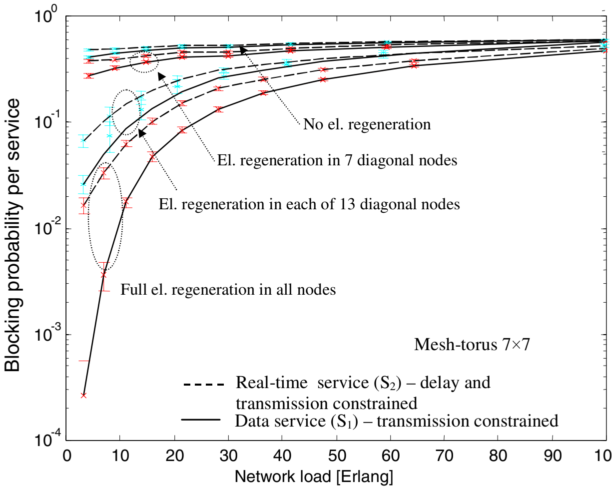

FIGURE 5. Blocking probability per service: DWP for different network architectures; $S_1[q_{\max}<60\text{dB}, d_{\max}<100\text{ tu}]$, $S_2[q_{\max}<60\text{dB}, d_{\max}<300\text{ tu}]$ (wavelength shifting at regenerative nodes only).

E. CONCLUSIONS

In this paper, we presented a generic approach to on-demand provisioning methods in selectively electronically regenerative, constraint-based routed, multi-service WDM networks, suitable for decentralized implementation. For the networking scenarios which assume heterogeneous architecture, sporadically available wavelength shifting capability and dynamic network operation, it has been shown that the methods proposed here particularly suit, since they can accommodate arbitrary number and type of path properties, related to the different network elements and services. Since the strategies shown here are based on flooding messages, which are evaluated, updated and generated at each network element, we used special features to reduce the computational complexity. The bounded requirements on feasible paths, service-differentiated network element characterization and reduced path set are some of the features which can significantly reduce the computational time. In particular for service-level guarantees, the service-differentiated network element characterization can naturally eliminate redundant information and it can provide accurate network state information.

With respect to selectively regenerative, opaque network architectures, we have revealed a new class of constraint-based path selection problems, namely those with network elements which at the same time deteriorate and improve the path performance. We have seen that decentralized, DWP-like protocols are crucial for such architectures, since they can efficiently capture multiple path properties "in service" and locally; they also avoid problems of methods with graphs and multi-objective optimization descriptors. While we have considered an architecture which uses electronic regeneration only if necessary (e.g. path performance insufficient for service), many other strategies to their deployment can be derived from DWP. For example, the objective may be to deploy regeneration along the minimum hop paths only, otherwise not; to use electronic regeneration for a particular service only; to minimize its usage, if the number of regenerating linecards is limited; etc. These strategies are of particular importance for the next generation optical networks that will deploy both all-optical and electronically regenerative architectures, for which the methods proposed here for the first time address the controversial issues related to the constraint-based routing and electronic regeneration within the optical layer.

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