Design of the Optical Path Layer in Multiwavelength Cross-Connected Networks

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Abstract—In this paper, we will discuss the wavelength requirement for optical networks based on wavelength-division multiplexing (WDM). A mathematical model, to represent the routing and wavelength assignment in optical networks with or without wavelength conversion, is described, and metrics are defined to express the performance. A new heuristic for routing and wavelength assignment is proposed and compared with the Dijkstra algorithm and with a solution based on integer linear programming. The different techniques are applied to a variety of network examples with different traffic loads.

I. INTRODUCTION

Current transport networks are mainly based on the plesiochronous digital hierarchy (PDH) and the synchronous digital hierarchy (SDH). Until now, the role of optics in SDH has been restricted to transmission. In [1]–[6], networks are proposed which use optical multiplexing and routing techniques to reduce the electronic processing bottleneck and to allow a more efficient usage of the bandwidth potential of the installed fiber-infrastructure. In this setup, electrical switch matrices are interconnected through optical paths which traverse a number of optical cross-connects. If the operations performed on the incoming optical path in each optical cross-connect remain very simple, transparent optical cross-connecting can be achieved. For example, by excluding wavelength translation, transparency can be obtained using state-of-the-art optical components [7]. By prohibiting wavelength translation and due to the reintroduction of physical limitations which were encountered in analog networks (as crosstalk, noise accumulation, etc.), routing restrictions are imposed on the optical layer which are nonexistent in the electrical layers. Hence, a specific approach to plan the configuration of this optical path layer is required.

In contrast to other publications where the virtual topology design is considered [8]–[11], this text is devoted to the design of the optical path layer. Given the configuration of the fiber-infrastructure and a set of nodes between which optical paths are requested, the routes and wavelengths are determined taking into account the limitations which are typical in an optical cross-connected layer. We focus on the issue of wavelength translation. Is wavelength translation an absolute requirement, what is the impact of not having it and what are the consequences on the design? Initial work in this area was presented in [12] and [13]. A simple heuristic, based on the Dijkstra algorithm, was applied on a more or less realistic example network. In contrast to the general feeling in literature, it was concluded that the difference in wavelength requirement between a network with and without wavelength translation is very limited and therefore not an absolute requirement. Other authors found similar results for regular networks [14], [15]. In this text, we propose a more systematic approach to the problem. We propose new routing techniques and apply them on larger and more heavily loaded networks.

In Section II, a description is given of the novel optical cross-connected networks and how they relate to the other network layers. In Section III, we define a mathematical model to describe the routing and wavelength assignment of optical layers with or without wavelength conversion. Successively, we propose several metrics to express the performance of routing and describe several routing techniques. A first approach is based on integer linear programming (ILP). As an alternative, a new heuristic algorithm is proposed which calculates the routing and wavelength assignment in networks without wavelength translation, maximizing wavelength reuse. Section IV is dedicated to some specific network examples. These will not only show the performance of the new heuristic but also reconfirm the limited difference in wavelength requirement between networks with or without wavelength translation. Finally, conclusions are drawn in Section V.

II. MULTIWAVELENGTH OPTICAL TRANSPORT NETWORKS

Several optical cross-connect (OCC) architectures are proposed in [1], [16], and [17] which combine optical-space division switching with WDM. Optical space switches route an incoming light signal to a desired outlet without conversion to the electrical domain. WDM allows a better utilization of the available bandwidth of the fibers and gives switching granularity in the optical domain, by routing distinct wavelengths from an incoming fiber to a different outlet fiber. Two different classes of multiwavelength OCC's can be distinguished: wavelength routing (WR) and wavelength translating (WT) cross-connects. WR cross-connects can route an incoming wavelength from an incoming fiber link to an output fiber link (where that specific wavelength is not in use). Basic components required to build WR cross-connects are optical space switches and wavelength filters. WT cross-connects allow wavelength shifts. A signal entering the node with a specifiwavelength can leave the node with a different wavelength. A key component to build a WT cross-connect is a wavelength convertor. Full optical channel transparency can
be achieved using all-optical wavelength conversion devices. In the OCC proposed in [16], wavelength conversion is established via the electrical domain using a receiver-transmitter pair, where the receiver or the transmitter or both are tunable. Depending on the functionality of the cross-connect, two important types of optical paths can be distinguished. In case of WT cross-connects, an optical path can have a different wavelength on each distinct fiber (virtual wavelength path, VWP) [3], [18]. In the case of WR cross-connects, each optical path has a fixed wavelength associated with it, and is therefore called a wavelength path (WP). In a VWP, wavelengths are allocated link by link in contrast to a WP where its wavelength has a global significance [3]. By reconfiguring a number of OCC’s, the network-operator is able to provide, cut off, or reroute optical paths between any two nodes in the network. To accommodate the optical paths a number of limitations have to be taken into account which are nonexistent in electrical networks:

1) **Functional Limitations**: Each WP has a fixed wavelength associated with it. Therefore, a new type of blocking occurs, denoted as wavelength blocking [19], if for the WP no route can be found with the same wavelength available on all the fibers of the route. WP’s with the same wavelength may cross in a node but they have to be link-disjoint. In the VWP scheme only capacity blocking can occur, which takes place if no route can be found with unused wavelengths on each fiber.

2) Transparency re-introduces also a number of physical limitations which were encountered in analog transmission systems. Different parasitic effects can be distinguished such as noise generation and spectral dependence of gain in optical amplifiers, crosstalk in optical switches, dispersion, nonlinearities like stimulated Raman scattering and four-wave mixing in optical fibers, etc. These effects become very important if an optical path has a long fiber length between its end-points or if it contains a large number of optical amplifiers and/or OCC’s [each including optical switches, wavelength (de)multiplexers, etc.]. Fig. 1 shows the effect of a limitation on the number of optical amplifications and cross-connect steps on the connectivity. For an example network, it is shown that the connectivity is seriously limited through a restriction on the number of optical amplifications (e.g., if ten amplifications are allowed, only 16% of all the possible node-pairs can be interconnected through an optical path). For other networks (e.g., smaller networks), a limit on the number of OCC’s (or hops) in an optical path can become the restricting factor.

The envisaged multilayer network concept combines the optical transmission and optical cross-connecting facilities which are described in the previous paragraph with electrical or digital cross-connecting (DCC). In both cases it is possible to split the cross-connect functionality of the network in two layers: the electrical path layer and the optical path layer. The connectivity of both layers is under the control of the network operator. Together with the physical layer, which consists in the fibers between the nodes, these layers represent the transport functionality of a combined electrical/optical cross-connected network. More detailed descriptions of this
multilayer model can be found in [20]–[22]. Optical paths can be considered as end-to-end connections in the optical path layer and form logical connections in the electrical path layer. Setting up or removing an optical path means the addition or removal of a logical connection in the electrical path layer. The optical path layer can be considered as a buffer between the electrical path layer and the fiber-infrastructure (or physical layer). It is used to fit the topology of the electrical path layer to the traffic requirements and it makes the topology of the electrical layer robust to errors occurring in the physical topology. Fiber cuts or node-failures can be survived through restoration or protection mechanisms in the optical path layer without changing the topology of the electrical path layer. Because of this independence between the physical topology and the electrical path layer the latter is also denoted as the virtual topology.

This network structure with two path layers is, in principle, not new. Similar constructions can be achieved if ATM-VP cross-connects are combined with SDH cross-connects or even within SDH where lower order paths are carried using higher order paths. The optical path layer offers, however, a bandwidth and transparency which is not achievable with electrical path layers.

The simplified routing and design of a regular virtual topology may be hindered due to the unbalanced load imposed on the regular structure in case of nonuniform traffic patterns. Several articles are published in the literature on the design of the virtual topology [8]–[11]. Algorithms are proposed which find a virtual topology (set of links) and routing of the traffic, given a network demand and a bound on the number of links. The links of this virtual topology are realized in the optical layer through the optical paths. If the physical infrastructure is an WDM passive star network, the mapping of the virtual topology on the physical layer is straightforward. Each link uses a unique wavelength (no wavelength reuse). If the optical path layer is composed of several OCC’s, this mapping is much more complex. All optical paths routes and wavelengths have to be determined taking into account all limitations on an individual optical path (e.g., limited length due to powerloss, noise, . . . ) and interactions between several optical paths (e.g., wavelength blocking, crosstalk).

An integrated approach is required to design a double layered network. In the virtual topology design, where it is decided which nodes have to be interconnected through optical paths, all implications to realize these optical paths have to be considered. Therefore, virtual topology and optical path layer design can be considered as two inseparable subproblems of multilayer planning.

III. DESIGN OF THE OPTICAL PATH LAYER

In this section, the design of the optical path layer is considered. Given a physical topology and a demand between a number of OCC’s, it is searched how the optical paths have to be accommodated. For a VWP network this requires for each path-request the calculation of the route1 (VWP-routing). Wavelengths have to be determined for each path in a WP network as well (denoted as WP-routing and wavelength assignment in [23], here as WP-routing). We define a mathematical model (partly based on the work of R. Ramaswami and K. N. Sivarajan described in [23]) and derive for WP and VWP networks a set of matrix equations using route and arc flows. Successively, we consider several solution approaches: a solution technique based on ILP and heuristic techniques which are applicable for larger and heavily loaded networks.

A. Mathematical Model

The optical path layer is modeled as an undirected graph \( G(V, E) \), where \( V \) is a set of vertices (size \( n \)) and \( E \) the set of edges (size \( m \))

\[
G(V, E) = \{v_1, v_2, v_3, \ldots, v_n\} \quad \text{with} \quad v_i = \text{vertex} \quad i \leq i \leq n
\]

\[
E = \{e_1, e_2, e_3, \ldots, e_m\} \quad e_j = v_pv_q\quad \text{edge} \quad 1 \leq j \leq m, 1 \leq p, q \leq n.
\]

Each vertex represents an OCC, each edge corresponds with a number of fiber pairs2 which lie between two OCC’s. The capacity vector \( \mathbf{K} \) (size \( m \times 1 \)) represents the dimensioning of the edges. The capacity of each edge is equal to the number of fiber pairs multiplied with the number of wavelengths (\( \lambda \)) which are available on each fiber

\[
\mathbf{K} = (k_j) \quad \text{with} \quad k_j \quad \text{the capacity of edge} \quad e_j \quad 1 \leq j \leq m.
\]

A source-destination pair, or sd-pair, is defined as a node pair with a demand3 larger than zero. \( S \) is the set of sd-pairs. The cardinality of this set is \( s \)

\[
S = \{v_i v_j \mid \text{demand between} \quad v_i \quad \text{and} \quad v_j \quad > \quad 0, 1 \leq i < j \leq n\}.
\]

The network-load (or the demand) is represented in the demand vector \( \mathbf{D} \) (size \( 1 \times s \)). Note that all elements of \( \mathbf{D} \) are nonzero. The offered network load \( (L) \) is the sum of all elements of \( \mathbf{D} \)

\[
\mathbf{D} = (d_i) d_i = \text{number of paths demanded by sd-pair} \quad i \leq i \leq s.
\]

B. VWP and WP-Routing Problem

In the routing problem, it is demanded to search for the routes to provide the given traffic load. This can be expressed using different formulations. Each of the formulations has its own decision variables and a set of equations which limit the number of solutions. In the flow formulation, the basic decision variables are the flows on the edge generated through each sd-pair. The route formulation starts with an enumeration of all routes between all sd-pairs and determines how many times a route is used.

1A route of a path is a sequence of fibers interconnecting the source with the destination.

2All traffic demand and links are assumed to be two way or bidirectional.

A fiber pair consists of two fibers which lie in opposite directions and which are incident to the same OCC’s. If several fiber pairs are incident to the same two OCC’s, they are represented by the same edge.

3The demand is expressed in the number of paths which are requested between each sd-pair. The capacity of a single path is one, requiring a single wavelength on each fiber of its route.
For the route formulation we need a number of new definitions: let \( \mathcal{R} = \{r_1, r_2, r_3, \ldots, r_r \} \) be the set of all possible routes, excluding the cycles, which interconnect each sd-pair of \( S \). The number of elements in this set is \( r \). The matrix \( \mathcal{Q} \) is the route-sd-pair incidence matrix (size: \( r \times s \)) and determines which route is incident to which source destination pair. The route-edge incidence matrix \( \mathcal{B} \) (\( r \times m \)) determines of which edges the routes are composed.

\[
\mathcal{Q} = (q_{ij}) \quad q_{ij} = \begin{cases} 1, & \text{if route } i \text{ is incident to sd-pair } j, \\ 0, & \text{otherwise} \end{cases} \\
\mathcal{B} = (b_{ij}) \quad b_{ij} = \begin{cases} 1, & \text{if } c_j \text{ is part of route } i \\ 0, & \text{otherwise} \end{cases}
\]

The length of a route is the number of edges it contains \( k_i = \sum_{j=1}^{m} b_{ij}, 1 \leq i \leq r \).

1) VWP-Routing Using Route Formulation (VWP-R): Routing in a VWP can be expressed using the routing vector \( \mathcal{F} \) (\( 1 \times r \)) and represents the number of times a route is used

\[
\mathcal{F} = (f_i) \quad \text{with } f_i \text{ number of paths which follow route } r_i, 1 \leq i \leq r
\]

\( \mathcal{F} \) gives a valid routing if the following matrix equations are valid: (1) the traffic-matrix is partly or completely provided and (2) the number of paths on each edge is limited to the number of wavelength channels \( \lambda \) multiplied by the number of fiber-pairs

\[
\begin{align*}
\mathcal{F} \cdot \mathcal{Q} & \leq \mathcal{D} \\
\mathcal{F} \cdot \mathcal{B} & \leq \mathcal{K}^T.
\end{align*}
\]

(1) (2)

The carried network load \( L^c \) and the mean path length \( E \) are defined as

\[
L^c = \sum_{i=1}^{r} f_i \\
E = \sum_{i=1}^{r} \frac{f_i k_i}{L^c}
\]

2) WP-Routing Using Route Formulation (WP-R): For a WP network we define \( \overline{\mathcal{W}} \) as the route-wavelength matrix with size \( r \times \lambda \).

\[
\overline{\mathcal{W}} = (w_{ij}) \quad \text{with } w_{ij} \text{ number of paths with route } r_i \text{ and wavelength } \lambda
\]

\( \overline{\mathcal{W}} \) corresponds with a valid routing and wavelength assignment if: (3) the traffic-matrix is partly or completely provided and (4) the number of paths carried by each edge on a single wavelength does not exceed the number of fiber-pairs

\[
\begin{align*}
\mathcal{I}_\lambda \cdot \overline{\mathcal{W}}^T \cdot \mathcal{Q} & \leq \mathcal{D} \\
\overline{\mathcal{W}}^T \cdot \mathcal{B} & \leq \frac{1}{\lambda} \mathcal{I}_\lambda \cdot \mathcal{K}^T.
\end{align*}
\]

(3) (4)

An alternative, but equivalent way to represent routing is the flow formulation [24]. The flow of an sd-pair on an edge is the traffic on this edge due to the demand between this sd-pair.

3) VWP-Routing Using Flow Formulation (VWP-F): The routing matrix \( \overline{\mathcal{X}} \) (\( m \times s \)) represents the amount of traffic flow due to each source-destination pair on all individual arcs

\[
\overline{\mathcal{X}} = (x_{ijk}) \text{ with } x_{ijk} \text{ traffic flow from sd-pair } k \text{ on edge } j \quad 1 \leq j \leq m, 1 \leq k \leq s.
\]

The following conditions have to be valid: (5) for each source destination pair the traffic requirement and flow-conservation must be valid in every vertex and (6) the total flow on and edge does not exceed its physical capacity

\[
\sum_{a_i \in \alpha(v_i)} x_{ijk} = \begin{cases} d_{k}, & \text{if } v_i = \text{source of sd-pair } k \\ -d_{k}, & \text{if } v_i = \text{destination of sd-pair } k \\ 0, & \text{otherwise} \end{cases} \\
\sum_{k=1}^{s} x_{ijk} \leq k_j \quad 1 \leq j \leq m
\]

(5) (6)

with \( \alpha(v_i) \) and \( \beta(v_i) \) the sets of edges which have \( v_i \) as origin and as destination vertex

\[
\alpha(v_i) = \{v_i v_q | v_i v_q \in \mathcal{E} \land 1 \leq q \leq n\}
\]

and

\[
\beta(v_i) = \{v_p v_i | v_p v_i \in \mathcal{E} \land 1 \leq p \leq n\}.
\]

4) WP-Routing Using Flow Formulation (WP-F): Similar to the VWP flow formulation a matrix \( \overline{\mathcal{Y}}(\lambda \times m \times s) \) can be defined representing the amount of traffic flow of each source-destination pair on each wavelength of an edge

\[
\overline{\mathcal{Y}} = (y_{ijk}) \text{ with } y_{ijk} \text{ the flow from sd-pair } k \text{ on wavelength } i \text{ of edge } j
\]

\[1 \leq i \leq \lambda, 1 \leq j \leq m, 1 \leq k \leq s.\]

Let \( d_{ik} \) be the part of the flow between sd-pair \( k \) which is assigned wavelength \( i(1 \leq i \leq \lambda) \). The following conditions have to be valid: (7) not more than \( d_{k} \) paths must be found, (8) a path entering a node with a wavelength, must have the same wavelength leaving the node. Hence, for each source-destination pair and for each wavelength, the traffic requirement and flow-conservation must be valid in every vertex \( (v_i) \). Equation (9) represents the capacity constraints

\[
\begin{align*}
\sum_{i=1}^{\lambda} d_{ik} & \leq d_{k} \quad 1 \leq k \leq s \\
\sum_{a_j \in \alpha(v_i)} y_{ijk} - \sum_{a_j \in \beta(v_i)} y_{ijk} = & \begin{cases} d_{zk}, & \text{if } v_i = \text{source of sd-pair } k \\ -d_{zk}, & \text{if } v_i = \text{destination of sd-pair } k \\ 0, & \text{otherwise} \end{cases} \\
\sum_{k=1}^{s} y_{ijk} & \leq k_j \quad 1 \leq j \leq m.
\end{align*}
\]

(7) (8) (9)
These four formulations represent all multicommodity flow problems. They cannot be divided into subproblems (considering every commodity individually), because the different commodities use the same underlying network and because the resources in this network (wavelengths) are limited. In an VWP-network, the different commodities are linked through the sharing of the common edges. In an WP network, where wavelength paths with the same wavelength must have disjoint routes, the correlation between the different commodities is even larger. Note that if the number of wavelengths is equal to one, WP-R and WP-F are equivalent to VWP-R and VWP-F, respectively. Table I compares the different formulations and gives the problem sizes (expressed through the number of variables and constraints). In the route-formulations (VWP-R and WP-R), the number of variables is proportional to the number of routes. In larger and highly connected networks, this parameter increases exponentially with the network size. In flow formulations, the number of variables is much lower. The number of constraints grows, however, similar as the number of routes in VWP-R and WP-R resulting in the same computational requirements. The route formulation has the important advantage that additional limitations can be imposed. Two types of limitations can be distinguished:

1) Limitations which exclude a number of routes from $\mathcal{R}$ (e.g., restrictions on the number of cross-connect steps or on the physical length of an optical path due to physical limitations). These limitations have the advantage that they decrease the problem size. This is illustrated in Fig. 1.

2) Restrictions which are imposed on a set of paths and not on an individual route (e.g., a bound on the power difference through the optical paths which are carried by the same fiber to limit cross-talk). These limitations are expressed in the VWP-R and the WP-R model through additional constraints and increase the problem size.

However, the comparison between WP and VWP-routing is important. The size of the VWP problem is independent of the number of wavelengths. This contrasts to the WP problem which grows quadratically with the number of wavelengths. The numerical example in Table I shows that the mathematical model of a WP network with ten wavelengths on each fiber is significantly larger than its VWP counterpart and shows how the physical restrictions in the optical path layer reduce the number of variables in the route formulations.

C. Performance Metrics

We define metrics to evaluate WP- and VWP-routing and derive upper bounds on the number of connections carried per wavelength.

Throughput ($\varphi$) is the percentage of the load which is set up by the routing algorithm ($\varphi = \left \frac{C}{E} \right \times 100\%$). The routing cost ($C$) is the cost to set up the network load (sum of the costs to set up individual paths). If the cost to use a single wavelength of a fiber is fixed to one, the cost of the routing will be proportional to the mean path length ($C = \frac{L}{E} \times E$). If enough wavelengths are available to route all paths via the shortest route, $E$ and $C$ will be minimal ($E_{\text{min}}$ and $C_{\text{min}}$, the numbers can be calculated using a shortest route algorithm as for example Dijkstra). If less resources (in this case wavelengths) are available, not all paths can be routed via the shortest routes and $E$ and $C$ will be larger than $E_{\text{min}}$ and $C_{\text{min}}$. The wavelength requirement ($L_{\text{min}}$) is the minimum number of wavelengths which is needed to set up all paths ($\varphi = 100\%$). Because wavelengths are a limited resource [15] this is an important parameter to compare WP with VWP. $L_{\text{c}}$ is the number of wavelength to set up all paths with a minimal length ($E = E_{\text{min}}$ and $C = C_{\text{min}}$).

An alternative way to represent routing performance is used in [23], where the offered and carried network load are expressed per wavelength through $\rho$ and $\rho^c$ ($\rho = L/L_{\text{c}}$). $\rho^c$ is a piecewise-linear function of $\rho$. The first part of the curve, where $\rho^c$ equals to $\rho$, is the nonblocking region ($\varphi = 100\%$). $\rho_{\text{max}}$ is the largest value of $\varphi$ in this nonblocking region. $\rho^c$ expresses how many times the same set of wavelengths is used in the network and is therefore a measure of the wavelength reuse. $\lambda_{\text{min}}$ is the smallest integer greater than or equal to $\frac{L}{\rho_{\text{max}}}$. For a VWP network, $\rho^c$ is only dependent on the quotient of $L$ and $\lambda$ (or $\rho$). This contrast to WP-routing where $\rho^c$ is influenced by $\rho$ and by the number of wavelengths. This can be derived using the routing equations, given in the previous paragraph, but can also be shown intuitively. Due to the differences between WP and VWP networks, $\rho^c_{\text{VWP}}$ and $\rho^c_{\text{WP}}$ will not always coincide.
there is only one wavelength on every fiber, there will be no difference between \( \rho^{VWP} \) and \( \rho^{WP} \). In [23], simple bounds are given for \( \rho \):

\[
\rho^{VWP} \leq \rho_{\max}^{(1)} = \frac{f}{E_{\min}}
\]

with \( E_{\min} \) the length of the shortest route in \( R \) and \( f \) the number of fiber-pairs in the network.

\[
\rho^{VWP} \leq \rho_{\max}^{(2)} = K
\]

where \( K \) is the maximum number of edge disjoint routes in the network.

For larger networks, however, these bounds fall in the blocking region \(( \rho \geq \rho_{\max} \)). Here we derive two upper bounds for \( \rho_{\max}^{VWP} \) which lie closer to the nonblocking region.

**Bound 1:**

\[
\rho_{\max}^{VWP} \leq \rho_{\max}^{(3)} = \frac{f}{E_{\min}}
\]

**Proof:** The best value for \( E \) while the throughput remains 100% is \( E_{\min} \) (all paths follow the shortest routes). \( E_{\min} \) can be calculated using a shortest route algorithm. There are \( f \cdot \lambda \) wavelength channels available in the network, where \( \lambda \) is the maximum number of fiber-pairs in the network. The maximum load is therefore limited by the following equation:

\[
L^* \leq f \cdot \lambda / E_{\min}. \quad \text{Divide this by } \lambda \text{ to obtain bound } \rho_{\max}^{(3)}.
\]

**Bound 2:**

\[
\rho_{\max}^{VWP} \leq \rho_{\max}^{(4)} = \frac{n_{fc}L}{L_{fc}}
\]

**Proof:** In [25], a cut is defined as a partition of the node set \( V \) in two parts: \( C \) and \( \bar{C} = V - C \). Each cut corresponds with a set of edges that have one endpoint in \( C \) and the other endpoint in \( \bar{C} \). The capacity of a cut is the number of edges in this set multiplied with the capacity of each arc. In our model this is equal to the number of fibers multiplied with the number of wavelengths. Each path from vertex \( v_i \) to vertex \( v_j \) with \( v_i \in C \) and \( v_j \in \bar{C} \) contains at least one edge of this cut which separates \( v_i \) from \( v_j \). \( D(C) \) is the sum of the demand of all the \( s \)-pairs with origin node lying in \( C \) and destination in \( \bar{C} \). Each path included in \( D(C) \) uses at least one wavelength of the cut. Hence, the capacity of the cut \( C \) must be larger than or equal to \( D(C) \). For each graph one or more cuts can be found for which \( D(C) \) divided by the capacity of \( C \) is maximal. We denote these cuts as the fundamental cuts. If a fundamental cut contains \( n_{fc} \) fibers and if \( D \) over this cut is \( L_{fc} \), the following expression has to be valid:

\[
L_{fc} \leq n_{fc} \lambda \quad \text{Divide this by } \lambda \text{ and multiply with } L \text{ to obtain } \rho_{\max}^{(4)}.
\]

If \( \rho = \rho_{\max}^{(3)} \) and \( \varphi = 100\% \), all fibers will be evenly loaded (all wavelengths will be used). This requires an optimal dimensioning of the network (perfect matching of the network to the load), and is very improbable. In most cases saturation will occur (if \( \rho \) is increased) before \( \rho = \rho_{\max}^{(3)} \). If \( \rho = \rho_{\max}^{(4)} \), some fibers (the fibers of the fundamental cut) block. Hence, \( \rho_{\max}^{(4)} \leq \rho_{\max}^{(3)} \) and the relation between \( \rho_{\max}^{(3)} \) and \( \rho_{\max}^{(4)} \) is a measure of the matching of the topology of the layer to the load.

\[\text{D. Linear Programming}\]

All of the equations defined in Section III-B are linear and all variables are constrained to be integer. ILP techniques can be used to find a global optimum of an objective function. The objective function can be to maximize the carried traffic for routing problems. For the route formulations this means:

\[
\text{VWP-R: } \max \sum_{i=1}^{r} f_i
\]

\[
\text{WP-R: } \max \sum_{i=1}^{r} \sum_{j=1}^{\lambda} w_{ij}.
\]

These functions assure solutions with maximum throughput, but the length of the calculated routes is unpredictable. Therefore, we introduce the routing cost in the objective function by using a weight function \((h_i)\) which favors the use of shortest paths.\(^5\) The objective functions become:

\[
\text{VWP-R: } \max \sum_{i=1}^{r} h_i f_i
\]

\[
\text{WP-R: } \max \sum_{i=1}^{r} \sum_{j=1}^{\lambda} h_i w_{ij}
\]

\[
h_i = (1 - h_i \ell_i) \text{ with } \ell_i \text{ the length of route } r_i \text{ and } h \text{ the weight factor.}
\]

\(^5\) By favoring the shortest routes, the calculation time to find a solution is reduced. Generally, shorter routes have a higher chance to be part of the optimal solution than longer routes.
The weight factor $h(h \geq 0)$ may not be too large, otherwise results are achieved with a very low routing cost but with a throughput less than 100%. The sum of all penalties must be smaller than one ($\sum_{i=1}^{n} h \cdot l_i \cdot f_i < 1$). A valid and easy way to calculate values for $h$ is, therefore

$$h = \frac{1}{2 \cdot L \cdot \ell_{\text{max}}} \quad \text{where } L \text{ is the network load and } \ell_{\text{max}} \text{ the length of the longest route in } R.$$ 

Upper bounds for the objective functions are calculated in [23] by dropping the integrality constraints and using linear programming. If not only bounds but also solutions have to be ILP, techniques are required. We use a branch and bound technique which optimizes integer problems by successive tightening of the variables to integer values starting from the continuous optimal solution. The feasibility of this method depends however largely on the size and the connectivity of the network.

**E. Heuristic Algorithms**

Because the WP- and VWP-routing problems are NP complete [15], [26], heuristic techniques are of large importance to design large scale networks. In initial work [12], [13] we used the Dijkstra algorithm, which is a shortest path algorithm. In the WP scheme, to extend an already found part of a route, only those arcs are considered which have a wavelength channel free which is available on all fibers of the already found part of the route. To find the routes and wavelengths of all paths, Dijkstra is applied sequentially. Therefore, the cost of each additional path is minimized without guaranteeing minimal cost of all paths. Dijkstra has the advantage that it can be used in a nonrearrangeable setup. The route of a new path is calculated without considering to rearrange the already found paths. This can be applied for restoration where only disturbed paths are rerouted or in a dynamic bandwidth allocation scheme where paths are added and removed without rerouting the already set up paths.

We present here a new algorithm, denoted as the heuristic routing and wavelength assignment algorithm (HRWA) which calculates a WP-routing minimizing the required number of wavelengths ($\lambda_{\text{WP}}$) and therefore maximizing the wavelength reuse ($\rho_{\text{WP}}$). This is contradictory to a minimum cost routing in most configurations, where the use of resources is minimized (in this wavelength channels) and not the wavelength requirement. Fig. 2 shows a flowchart of the algorithm. In Step 1, a minimal cost routing is searched with an, as low as possible, wavelength requirement, using a modified version of the Yen Algorithm. In Step 2, the needed number of wavelengths is decreased through rerouting of a number of paths (this may result in some routing cost penalty or longer routes). Step 2 is repeated until no further improvement (to lower $\lambda$) is possible.

**IV. Application**

Here we consider two networks with more or less realistic loads. The performance of the different (V)WP-routing techniques is investigated. To investigate the importance of wavelength blocking, the wavelength requirement is calculated for networks with and without wavelength conversion.
A. European Optical Network

Figure 3 shows the EON, which is a 19-node network interconnected by a dense fiber-infrastructure [27]. The network is considered in the case of normal operation mode and in the case of single link-failures. The calculations are repeated for several traffic-loads ranging from 100–492 optical paths (traffic patterns s1–s3), reflecting the expected traffic-growth between all nodes.

1) WP- and VWP-Routing in Normal Operation Mode:

Figure 4 shows the performance of the different WP and VWP-routing algorithms when the network is loaded with 492 paths between 110 sd-pairs (traffic pattern s3). In Fig. 4(a), the calculation times are depicted. Routing in the WP scheme using ILP is very time consuming. The difference with VWP-routing using ILP increases if more wavelengths are considered (this confirms the quadratic dependency of $\lambda$ in the problem size of WP-routing). In Fig. 4(b), the routing cost (and proportional to this the mean path length) is represented as a function of the number of available wavelengths. Shorter routes become available when more wavelengths are present in the network. The best solutions are achieved with ILP. To compute the ILP figures, the route formulation is used; moreover, to keep calculation times reasonable, only a subset of all routes is considered (only the 25-shortest routes for each sd-pair). Increasing the number of considered routes (to 50 and 100) augmented calculation time but didn’t result in better solutions. At least ten wavelengths are required in both the VWP and the WP scheme. With this number of wavelengths, there is a very small difference in path length (WP longer than VWP). This difference disappears if more wavelengths are available (>10). Fig. 4 illustrates the good performance of the HRWA algorithm. Results are only shown for one wavelength because this algorithm minimizes the number of wavelengths. The same degree of wavelength reuse as WP-ILP ($\lambda_{\text{min}} = 10$) is achievable with a path length penalty which is less than 2% and calculation requirements comparable with Dijkstra. Fig. 5 shows how the HRWA algorithm searches in an initial phase for the minimal cost routing, which requires the lowest number of wavelengths (Step 1 and the first part of Step 2). In a second phase, the wavelength reuse is maximized with consequently some routing cost penalty (second part of Step 2). Table II summarizes these results of traffic pattern s3 and gives numbers for other uniform and nonuniform traffic patterns. For all traffic patterns (s1, s2, s3, and uniform load), the performance of each WP- and VWP-routing algorithm is expressed using the metrics defined in Section III-C ($\lambda_{\text{min}}, \lambda_{\text{c}}, \rho_{\text{max}}, \cdots$). For traffic pattern s3, the largest wavelength reuse ($\rho_{\text{max}}^{(3)}$) achieved for WP and VWP is 24.6. This approximates $\rho_{\text{max}} = 26.35$ (the upper bound enumerated using the fundamental cut). The upper bound [$\rho_{\text{max}}^{(3)} = 56$], which is defined in [25], is far from achievable without blocking. Traffic pattern s2 gives similar results as pattern s3. With ILP no difference appeared between WP and VWP and the good performance of the HRWA algorithm is confirmed. For this pattern Dijkstra performs even better for WP’s than for VWP’s [this could also be noticed in Fig. 4(b)]. A possible justification for this is the better spreading of traffic, which is typical to WP-routing, making—in a nonoptimal technique as Dijkstra—WP-routing less sensitive for congestion. The results of traffic pattern s1 are very similar for all algorithms, $\lambda_{\text{min}} = 3$ and $C_{\text{max}} = C_{\text{min}}$. The main reason for this is the large difference between $\rho_{\text{max}}^{(3)}$ and $\rho_{\text{max}}^{(4)}$. The topology, which is dimensioned for the s3 traffic, is for this s1 pattern far from optimal [compare $\rho_{\text{max}}^{(3)}$ and $\rho_{\text{max}}^{(4)}$ with corresponding values of the s3 pattern]. Saturation occurs, therefore, very soon (at low $\rho$ when $\rho$ is increased) and in a limited part of the network. This explains also why $C_{\text{max}}$ is equal to

To compute the ILP solutions we use the optimization subroutine library (OSL) of IBM which has been linked with our optical network simulator WDMSim.
Routing cost, (- mean path length),
c lower bound = 10
Fig. 5. Performance of the HRWA algorithm applied on the EON topology (network load: s3).

\[ C_{\text{min}} \]

From the moment there is enough capacity available and the bottlenecks are removed, and minimal cost routing is possible. A WP network behaves in these circumstances completely similar to a VWP network: capacity blocking (or congestion) occurs in a part of the network before wavelength blocking is encountered. The uniform traffic pattern has more sd-pairs \((171 = N \times (N - 1)/2 \text{ with } N \text{ being the number of nodes})\), but a lower load than pattern s3. Because the speed of the heuristics is mainly determined by the network load,7 heuristic techniques work faster for the uniform pattern than for s3. The ILP-algorithms [number of variables depend on the number of sd-pairs \((s)\) and not on the network load \((L)\)] work faster for the s3 pattern.

2) Survivability Calculations: The availability of the network is computed by generating all possible link-failures and calculating the percentage of all paths which can be restored. An availability of 100% means that all paths can be restored if any link is cut. For WP's, similar as in [14] and [15], two different restoration techniques are distinguished: if the restoration path may have another \(\lambda\) than the disturbed path (case WP-a) and secondly if the restoration path must have the same \(\lambda\) (case WP-b). In case WP-a, restoration of a path may require tuning or selecting another first transmitter. To calculate the routes in normal operation mode, we use the same algorithms as in the previous section (ILP, Dijkstra, and HRWA). To find the restoration routes and wavelengths, we use Dijkstra. In Fig. 6, the effect of the number of wavelengths on the availability is shown for VWP, WP-a, and WP-b. The difference between WP-a and VWP is very small. WP-b behaves much worse because the chance to find an alternative route at the same wavelength is very low. There is, however, a substantial influence of the used algorithm. In the WP-b scenario, Dijkstra resulted in a better performance than the HRWA algorithm. HRWA fills the lowest wavelength channels maximally and leaves the highest channels unassigned. In the WP-b scheme, these unassigned or spare wavelengths cannot be used in case of failures because the wavelengths of the disturbed paths cannot be changed. If Dijkstra is used, the wavelength reuse of the lowest wavelength channels is less. This gives, in the WP-b scheme, higher survivability in comparison with HRWA.

B. National Network

A second network which is considered is a possible topology for a national network and is obtained from the planning department of Belgacom [28]. Besides the physical topology, a nonuniform load is used; ±50% of the load is traffic between adjacent nodes, and a substantial part of the remainder is long distance traffic (e.g., sd-pairs exist with routes traversing at least ten hops). Results are given in Table III. For the VWP network, 11 wavelengths are required to set up all the paths. If the HRWA algorithm is used, 12 wavelengths

\[ C_{\text{min}} \]

This is mainly due to the sequential character of the heuristics, where each path is considered individually.
TABLE II
SIMULATION RESULTS OF THE EON APPLYING DIFFERENT NETWORK LOADS

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\[(1)\text{x-hop traffic: number of paths which have a shortest length of x hops (e.g., 0-hop load= traffic to adjacent OCCs)}\]

\[(2)\text{Not computable}\]

are required for the WP implementation of the network (cost penalty <3%). If 11 or 12 wavelengths are considered, the number of wavelengths multiplied with the routes (r) is too large to solve the problem with ILP. If the problem size is decreased (e.g., if \(\lambda\) is reduced to four and the number of fibers is tripled), the problem becomes computable with ILP and the same performance (routing cost) is achieved as the VWP solution with \(\lambda = 12\).

C. Lessons We Learn from These Simulations

- WP networks are far more difficult to calculate than VWP networks. If larger numbers of wavelengths are considered on each fiber, calculation time becomes very long for larger and heavily loaded networks and heuristic techniques are required.
- The HRWA algorithm performs well. It maximizes wavelength reuse and reserves the highest wavelengths for failure restoration, assuring a high survivability in the WP-a scheme.
- In networks with a bad matching of the load to the network-topology or vice versa, capacity blocking can occur before wavelength blocking takes place. This matching can be predicted using the upper bounds defined in Section III-C. If a large difference exists between \(\rho_{max}\) and \(\rho_{max}\), some links of the network are saturated (capacity blocking) before wavelength blocking occurs.
wavelength translation is not necessary in every hop. A hybrid solution where wavelengths are only translated in specific nodes (e.g., where the paths are electrically regenerated) gives no significant drawbacks.

ACKNOWLEDGMENT

The authors thank Belgacom for providing a network topology example.

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