Planning Flexible Optical Networks Under Physical Layer Constraints

K. Christodoulopoulos, P. Soumplis, and E. Varvarigos

***Abstract*—We consider the planning problem of a flexible optical network. Given the traffic matrix and the transponders' feasible configurations that account for the physical layer, we formulate the planning problem considering both the use or not of regenerators. Demands are served for their requested rates by choosing the route, selecting the transmission configuration, breaking the transmissions in more than one connection and placing regenerators, if needed, and allocating the spectrum to them. The objective is to serve the traffic and find a solution that is Pareto optimal with respect to the maximum spectrum used and the cost (number and type) of transponders used. The problem definition and the proposed algorithms are general and applicable to flex-grid as well as fixed-grid networks. We start by presenting algorithms based on integer linear programming formulations for transparent and translucent networks (without or with regenerators) and we continue by presenting heuristic algorithms. Using input driven by transmission studies on optical orthogonal frequency-division multiplexing (OFDM)-based networks we evaluate the performance gains that can be obtained by an OFDM over a mixed line rate fixed-grid WDM optical network.**

***Index Terms*—Flex-grid; Flexible optical networks; planning (offline) problem; Routing and spectrum allocation; Transparent and translucent networks.**

I. Introduction

The continuous growth of consumers' IP traffic, fed by the generalization of broadband access [through digital subscriber lines (DSL) and fiber to the home (FTTH)] and the emerging rich-content high-rate and bursty applications, such as video-on-demand, HDTV, and cloud computing, can be met only with the abundant capacity provided by optical core and metro networks. For the future, it is expected that the traffic will not only increase in volume (traffic increased by 34% on average in 2012 [1]) but will also exhibit high burstiness, resulting in large variations over time and direction. To cope with the increasing capacity requirements, WDM systems target the employment of higher rate and improved distance transmissions. However, the rigid granularity of WDM systems leads to inefficient capacity usage, a problem expected to become more significant with the deployment of the higher channel rate systems.

To improve system efficiency, recent research efforts have focused on architectures that support variable spectrum connections. Typically, wavelength routed WDM networks operate over the ITU-T grid, that is, connections are established over a 100 or 50 GHz frequency spaced grid. Flexible optical networks (elastic is another term used to describe such networks) assume the use of tunable transponders and a flexible spectrum grid or *flex-grid* [2]. Flex-grid's granularity is much finer than that of standard WDM systems: the spectrum is divided into spectrum slots (e.g., 12.5 GHz) that can be combined to create channels that are as wide as needed. Tunable optical transponders, also called *bandwidth variable transponders* (BVTs) or software defined transponders [3], have recently been proposed. The key difference to standard transponders is that they can adapt several transmission parameters, such as the transmission rate, the modulation format, and the spectrum that they use. In a flexible network, a BVT uses just enough spectrum to serve the demand and every bandwidth-variable optical cross-connect (OXC) [4] on the path establishes a cross-connection with sufficient spectrum to create an appropriately sized end-to-end connection, what we call a *flexpath*.

A number of networking paradigms adopting the flexible approach have emerged in the past few years. The spectrum-sliced elastic optical path network (SLICE), presented in [5,6], utilizes optical orthogonal frequency-division multiplexing (OFDM) to distribute the data on several low data rate subcarriers (multicarrier system). Single-carrier systems may also operate in a flex-grid manner, such as the flexible-WDM (FWDM) architecture considered in [7]. Focusing on the spectrum as a flexible resource, algorithms for planning flexible networks have been proposed [6–10]. The related problem is referred to as *routing and spectrum allocation* (RSA) or as *routing, modulation level and spectrum allocation* (RMLSA), when the modulation level of each connection can be also chosen elastically.

In this paper we propose impairment-aware RSA (IA-RSA) algorithms for planning transparent and translucent flexible optical networks under physical layer impairments. We consider a flexible network that encompasses a slotted flex-grid network and BVT transponders with tunable transmission parameters. We assume that we have a *physical feasibility function* that identifies the reach at which a transmission is feasible, given the parameters that

Manuscript received April 22, 2013; revised July 24, 2013; accepted September 4, 2013; published October 31, 2013 (Doc. ID 187164).

K. Christodoulopoulos is with the School of Computer Science and Statistics, Trinity College Dublin, Dublin, Ireland (e-mail: christok@tcd.ie).

P. Soumplis and E. Varvarigos are with the Computer Engineering and Informatics Department, University of Patras, Patra, Greece.

http://dx.doi.org/10.1364/JOCN.5.001296

are under our control, such as the rate, the spectrum used for the transmission, and the guardband left from its spectrum-adjacent flexpaths. Feasibility here refers to the physical layer and having acceptable bit-error ratio or acceptable quality of transmission (QoT). The physical feasibility function can be obtained experimentally or using analytical models [11,12].

Given a BVT and since the modulation and the spectrum used are selected from discrete sets, we have certain feasible transmission configurations (or tuples) for this transponder. These feasible transmission tuples are used as input to our algorithms and incorporate in their definitions the consideration of the physical layer impairments, making the algorithms we will develop impairment aware (IA). Although in the simulation experiments presented here we use transmission tuples that are based on physical layer studies on OFDM optical networks [11], the proposed algorithms are general and can be used in any type of network (flex-grid or fixed-grid), as long as the input in the form of feasible (reach, rate, spectrum, guardband, cost) transmission tuples or tuples with fewer parameters is provided. For example, the proposed algorithms can be used, with appropriate definitions of the physical feasibility function, for planning flexible networks under reach-modulation format constraints, as examined in [6,8,9], or even for planning data-rate-flexible or mixed-line-rate (MLR) fixed-grid WDM networks, as examined in [13] and [14], respectively.

A demand for a given source–destination pair is served by establishing one or more optical connections. It is the role of the planning algorithm to decide how to serve each demand, and, in particular, decide if and how to break it into connection(s), select the configuration(s)/tuple(s) to be used by the transponder(s), and allocate path(s) and spectrum to those accordingly. If the network supports regenerators (translucent network), the algorithm also has to identify the regeneration nodes for serving the demands. As we can see from the above, the selection of the configurations to be used by the BVT transponders is included in the RSA problem, as it should be, since transmission parameters interrelate the transmission reach with the spectrum used, the rate, and the guardband. The objective is to serve the traffic and find solutions that are Pareto optimal with respect to the two optimization criteria considered: a) the maximum spectrum used and b) the cost (type and number) of transponders used. We develop algorithms based on integer linear programming (ILP) formulations for transparent and translucent networks and also heuristics that utilize the simulated annealing meta-heuristic.

We evaluate the performance of the proposed algorithms and through them the gains that can be obtained by a flexible over a fixed-grid optical network. The feasible transmission tuples used in our simulations were derived from studies on OFDM optical networks [11]. Our results indicate that the proposed simulated annealing heuristics can trade-off execution time for performance and can yield near optimal performance, comparable to that obtained by the ILP algorithms, at least for the small size network experiments for which we were able to track optimal ILP solutions. In studying realistic network planning problems we observe the significant gains that can be obtained by the OFDM flexible over a MLR fixed-grid WDM network.

The rest of the paper is organized as follows. In Section II we report on the related work. In Section III we formally define the planning problem in a flexible optical network under physical layer constraints. In Section IV we present our solutions and, in particular, the ILP formulations to solve the planning problem for transparent and translucent networks and also our heuristic algorithms. In Section V we present our performance comparison results. Our conclusions follow in Section VI.

II. Related Work

Flexible optical networks have received increasing attention during the past few years, with many research efforts focusing on the algorithms required to support the efficient planning and operation of such networks [6–10,15–19].

Planning a flexible optical network [6–10] is typically performed by serving the demands for their requested rates, which are assumed to be known in advance, by elastically allocating spectrum to them. Typically the objective of the planning problem is to serve all demands and minimize the maximum spectrum used, a problem referred to as RSA or RMLSA. In [6], the authors present a scheme to adaptively allocate the spectrum according to the transmission distance so as to make better use of network spectral resources. In our previous work [8], we provided an optimal RMLSA algorithm based on ILP. Since the RSA (and its extension, the RMLSA) problem is NP-hard a heuristic algorithm was also proposed to provide solutions for large problem instances. An alternative ILP formulation that is based on a precomputed set of channels that represent contiguous spectrum slots is presented in [9]. Reference [10] considers the RSA problem in the SLICE network and obtains analytical results for rings and other regular topologies. The RSA problem in flexible single carrier optical networks (FWDM) is examined in [7].

In addition to the planning, the operational phase of the flexible network has also been studied [15–19]. In the operational phase, dynamic variations in traffic are absorbed by establishing and releasing connections or by elastically expanding and contracting the spectrum allocated to the existing ones.

Other works on spectral efficient optical networks that follow, however, a fixed-grid approach include [13,14]. In [13] the planning problem of a MLR-WDM network is examined. MLR networks offer the advantage of multigranular transmission options that can trade-off performance (reach rate) to cost, as opposed to standard single rate WDM systems. Data-rate tunable transponders for fixed-grid WDM networks are considered in [14], showing performance gains similar to those of MLR networks but using a single transponder model.

An issue that has not yet been fully considered in flexible networks is the effect of the physical layer on the QoT. In standard fixed-grid WDM networks the IA-RWA problem, where physical layer constraints are accounted for during connection establishment, has received considerable attention [20,21]. The majority of algorithms proposed for flexible optical networks either do not consider physical layer limitations [7,10] or incorporate simple reach-modulation format constraints to capture the effect of the physical layer [6,8,9]. Moreover, these references that focus on planning flexible networks consider only transparent connections. However, a lengthy end-to-end connection can be regenerated and established in a multisegment manner in order to keep the QoT acceptable. The regenerator at the end of a segment serves as a “refueling station” that restores signal quality. These types of optical networks, where some demands have to go through a sequence of 3R regenerators, are referred to as translucent networks [22]. Although much work has been done on translucent fixed-grid WDM networks, the corresponding problem for flexible networks has not, to the best of our knowledge, been addressed so far.

The novelty of our proposed solutions compared to previous works is fourfold. First, we provide general algorithms that take generic parameters as input. In particular, the input comes in the form of feasible transmission configurations (the physical feasibility function) of the transponders used in the network. The physical layer impairments are incorporated in the definition of these configurations, so that the proposed algorithms are impairment-aware. Our performance experiments use realistic transmission specifications based on physical layer studies of OFDM-based networks [11], but the problem definition and the proposed algorithms are general and applicable to any type of flexible as well as fixed-grid (standard WDM or MLR) network. Note that our algorithm, in addition to allocating routes and spectrum, also selects the transmission configurations, which includes more parameters than previously proposed solutions. Second, previous algorithms considered only a single connection per demand (source–destination pair), while the proposed algorithms decide also on how to break the demands into multiple connections, if needed. Third, the proposed algorithms consider the use of regenerators (if these are allowed). Finally, the objective of previously proposed algorithms was to minimize the maximum spectrum used, while the new algorithms consider both the spectrum and the cost of transponders used in a multiobjective optimization formulation.

III. Problem Statement

We start by describing the planning problem in a flexible optical network under physical layer impairments; the algorithms to solve it are presented in the following section.

We are given an optical network $G = (V, E)$, where V denotes the set of nodes and E denotes the set of (point-to-point) single-fiber links. We are also given the actual (physical) lengths D_l of the links $l \in E$. We assume that the spectrum is divided into spectrum slots of F GHz, where one spectrum slot corresponds to the switching granularity of the flexible network elements (flex-grid switches and BVTs). We assume an *a priori* known traffic scenario given in the form of a *traffic matrix* Λ in Gbps, where Λ_{sd} denotes the requested capacity for demand (s, d), that is, from source s to destination d.

The traffic is served by BVTs. A BVT of cost c can be tuned to transmit r Gbps using bandwidth of b spectrum slots and a guardband of g spectrum slots from the adjacent spectrum flexpaths to reach l km distance with acceptable QoT. More formally, we assume that a specific transponder of cost (type) c is characterized by its physical feasibility function f_c that gives the reach $l = f_c(r, b, g)$ at which it can transmit with acceptable QoT based on the parameters r (rate), b (spectrum), and g (guardband) that we can control. This function captures the physical layer impairments, assuming worst-case contribution for the interference-related impairments (four-wave mixing, cross-phase modulation, cross-talk), and can be obtained either through experiments or using analytical models [11,12]. Figure 1 shows an example of a physical feasibility function without displaying (for illustration purposes) the guardband parameter g, assuming $F = 6.25$ GHz and a transponder capable of transmitting up to 600 Gbps in 50 GHz. Note that defining a specific rate r and spectrum b incorporates the choice of the modulation format of the transmission. Figure 2 shows the same function f_c, but this time we suppress the spectrum parameter and show the modulation format used for each transmission. Note that the above definition is general, making the proposed algorithms applicable to any type of flexible or even fixed-grid optical network. We will comment further on the generality of the problem definition and the proposed algorithms in Subsection III.A.

Using the function f_c we define a (reach, rate, spectrum, guardband, cost) transmission *tuple*, $t = (l_t, r_t, b_t, g_t, c_t)$, which corresponds to a feasible transmission configuration. The term “feasible” is used to signify that the tuple definition incorporates the limitations posed by physical layer impairments. The cost parameter is used when we have different types of transponders with different capabilities. We also assume that the transponders have certain

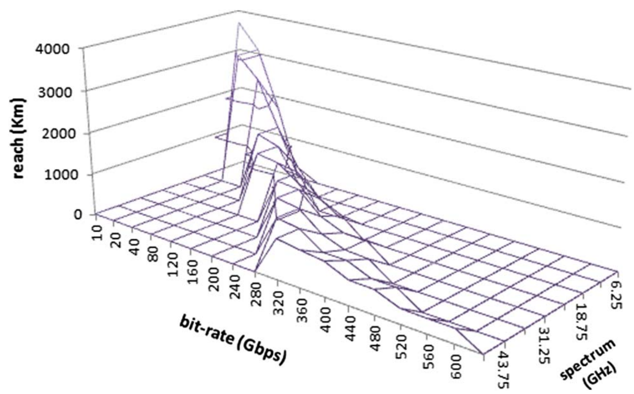

Fig. 1. Transmission reach as a function of the rate and spectrum used for a specific flexgrid transponder.

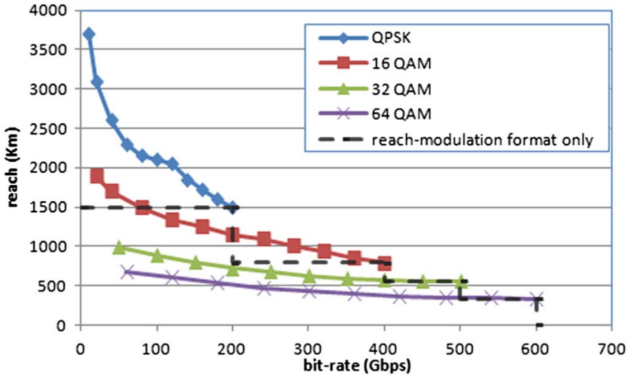

Fig. 2. Transmission reach as a function of the rate and modulation format used by a specific flexgrid transponder.

limitations in their capabilities, which can be of the following forms: the maximum symbols per second (baud rate), and/or the maximum modulation format, and/or the maximum spectrum used, and/or the maximum transmission rate. Given the transponders' limitations, and since the modulation format and the spectrum are selected from discrete sets, we have a certain set of feasible transmission configurations for the transponders. We denote by T the set of transmission tuples (referred to as the *tuple lookup table*).

To serve a demand (s, d) we establish one or more optical connections between the source s and the destination d. The number of connections depends on the demanded capacity, the capabilities of the transponders, and the transmission tuple(s) used. It is the role of the IA-RSA algorithm, described in the following section, to decide how to serve each demand, and in particular decide how to break each demand in connection(s), identify the configuration(s)/tuple(s) that the transponder(s) will use, and allocate path (s) and spectrum slot(s) to those connection(s) accordingly. As can be seen from the above, the selection of the transmission configuration to be used for each connection is included in the RSA algorithm, since transmission parameters are interrelated to the transmission reach, the rate, and the required spectrum and guardband.

In transparent networks each connection is a *transparent flexpath*, that is, an end-to-end transparent optical connection. A flexpath is served by a single BVT and has to utilize the same spectrum segment (spectrum slots) throughout its path (the *spectrum continuity constraint*). In translucent networks, where optical regeneration is performed at one or more intermediate nodes, the flexpath is terminated at the regeneration node and a new flexpath is initiated, to create an end-to-end *translucent connection*. Thus, a connection in a translucent network can be a single transparent flexpath, or a sequence of transparent flexpaths. We assume that a regenerator is implemented using a transponder (connecting the receiver–transmitter back-to-back) and thus the total number of transponders required for a translucent connection is equal to the number of transparent flexpath segments that comprise it. The calculations can be modified accordingly to capture the case where the cost of regenerators is not equal to the cost of the transponders. Note that the spectrum continuity constraint continues to apply over each individual transparent flexpath segment of the translucent connection. No spectrum overlapping is allowed among the flexpaths at a given time instant (the *nonoverlapping spectrum assignment constraint*). For the remainder of the paper the term "connection" will refer to the end-to-end communication, which could be transparent or translucent, that is, consisting of a transparent flexpath or a sequence of transparent flexpaths.

To have acceptable QoT at the specific reach, a transmission tuple t includes a specific guardband value g_t to keep the interference from the spectrum-adjacent flexpaths at an acceptable level. Guardband g_t is defined assuming a worst-case interference from the spectrum-adjacent flexpaths. Also note that g_t corresponds to the spectrum space (in slots) that has to be left at both spectrum edges of the flexpath that uses t individually from every spectrum-adjacent flexpath along its path. In the general case, different flexpaths can require different guardband values. Guardband slots can be reused by adjacent flexpaths, as opposed to data spectrum slots that cannot be shared (according to the non-overlapping spectrum assignment constraint). The constraint is that the slot space left between two spectrum-adjacent flexpaths has to be at least equal to the maximum of the two respective guardband values.

Given the network topology, the traffic matrix, and the specifications of the BVTs in the form of the transmission tuple lookup table (the feasible transmission configurations), the objective is to serve the traffic and minimize a function of the maximum spectrum and the cost of the transponders used. Figure 3 presents an instance of the planning problem.

A. Generality of the Problem Definition

Although in the simulation experiments to be presented in Section V we use transmission attributes that are derived from physical layer studies on OFDM optical networks [11], the problem definition and the algorithms to be proposed are general and can be used for planning different types of optical networks, not necessarily OFDM-based, including other types of flexible as well as fixed-grid (standard WDM) networks. The only requirement is the ability to express the feasible reach of a transmission as a function of the rate, spectrum used and guardband required or a function with even fewer parameters. This physical feasibility function should take into account the physical layer impairments, including worst-case contribution for interference. In other words, the requirement is to be able to describe the feasible transmission options in the network with (reach, rate, spectrum, guardband, cost) tuples or fewer parameters. Note that instead of having in the input tuples the spectrum and the rate parameters, we can replace one of them by the corresponding modulation format. So, the proposed algorithms are applicable for planning networks with reach-modulation format constraints and constant slot guardbands as in [6,8,9]. Note that if we use a function for reach that takes into account only the

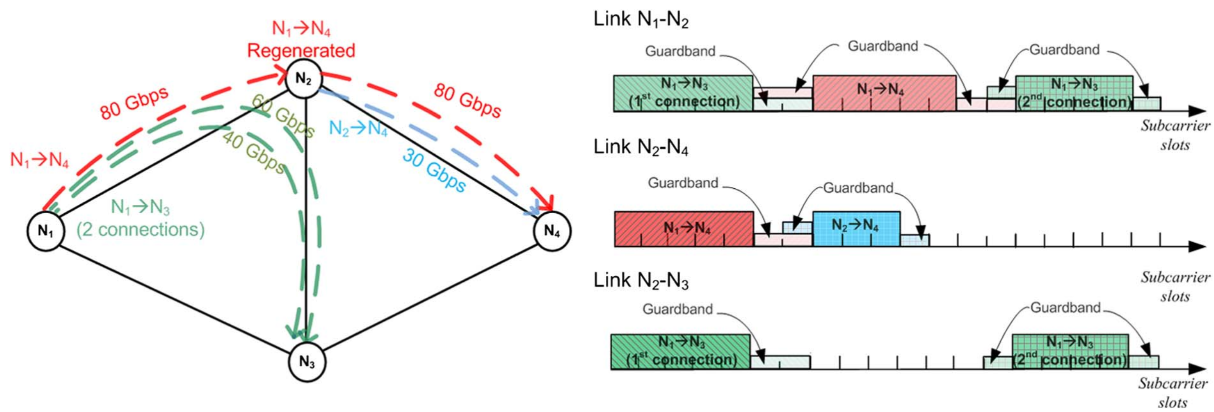

Fig. 3. Flexgrid network with four nodes and three source–destination demands and the related spectrum slot allocation on the links used. Connections can be established in several transmission configuration options. Demands can be broken into multiple connections that can be regenerated at intermediate nodes (forming a sequence of transparent flexpaths). The guardband that is left between two adjacent flexpaths has to be at least equal to the maximum of the two guardband values of the spectrum-adjacent flexpaths. The non-overlapping spectrum assignment constraint pertains only to the data-transferring spectrum slots. The spectrum continuity constraint is applied to the transparent flexpaths (subpaths) of the connections.

modulation format we reduce substantially the feasible transmission options (see in Fig. 2 the "reach-modulation format only" line, where we require acceptable reach for all transmissions using a specific modulation format). Algorithms using such input, e.g., [6,8,9], would not be able to explore all transmission options that can improve the network performance.

Another interesting feature of the presented problem formulation is that it can include even MLR [13] or data-rate-flexible networks [14] that operate over fixed-grid WDM. This can be done by defining as feasible only transmission tuples in which the spectrum parameter is constant and equal to the granularity of the fixed spectrum grid, i.e., 50 GHz. Then the transmission limitations posed by physical layers are captured by the reach–rate–cost parameters for the different types of MLR transponders, and the guardband is set equal to zero (assuming that it is included in the wavelength slots). In this model, the number of different transmission tuples equals the number of different MLR transponders [13] or the number of different modulation formats supported by the rate-tunable transponders of [14]. In the comparison results of Subsection V.B we apply the developed algorithms both to the case of a flexible and of a fixed-grid network, so as to compare these systems in a unified manner.

IV. Impairment Aware Routing and Spectrum Allocation Algorithms

In this section we describe the proposed algorithms for the IA-RSA problem in spectrum-flexible networks. We initially present a preprocessing phase, which is common to both the ILP and the heuristic algorithms presented later, for calculating a set of Pareto optimal (nondominated) path-transmission tuple pairs that are considered as candidate solutions. We then present, in Subsection IV.B, an ILP [23] formulation for planning transparent and translucent optical networks. The proposed IA-RSA algorithm uses a multiobjective function to find solutions that are Pareto optimal with respect to the spectrum used and the cost (type and number) of the transponders. The IA-RSA problem under study is NP-hard, since the simpler (without impairments) spectrum allocation problem is the same as the one in [8], and thus, in Subsection IV.C, we also propose a heuristic algorithm that is based on serving each demand sequentially, on a given ordering, and use simulated annealing to search among different orderings.

A. Preprocessing Phase: Computing the Set of the Candidate Path-Transmision Tuple Pairs

The preprocessing phase computes the set of candidate path-transmission tuple pairs for serving the requested demands. The paths defined here include also the regeneration nodes. Algorithms that do not use any set of predefined paths, but allow routing over any feasible path and regeneration at any node (using multicommodity flow formulations) could also be devised. These algorithms are bound to give at least as good solutions as the algorithms that use precalculated paths, such as the ones proposed here, but use a higher number of variables and constraints. However, the optimal solution can also be found with an algorithm that uses precalculated paths, given a large enough set of paths. We will comment more on the optimality of the solution in Subsection IV.A.1.

For each demand (s,d) we precalculate k paths, using a variation of the k-shortest path algorithm. We let P_{sd} be the set of candidate paths for (s,d) and $P = \cup_{(s,d)} P_{sd}$ be the set of all candidate paths.

Let Λ_{sd} be the capacity requested for demand (s,d) and consider a path $p \in P_{sd}$. Based on the length of the links of path p, we identify the configurations (tuples) that can be used by the transponders over that path. In particular, we examine if a transponder configuration, given as a (reach, rate, spectrum, guardband, cost) transmission tuple

$t = (l_t, r_t, b_t, g_t, c_t)$ of the lookup table T, has acceptable transmission reach: the reach l_t has to be higher than the length of the path p for transparent networks, and higher than the longest link of the path for translucent networks. For each transmission tuple t that has acceptable transmission reach for path $p \in P_{sd}$ we define a *path-transmission tuple pair* (p, t) that is a candidate option to serve demand (s, d) in the flexible network. Note that in our solution if we break the demand into more than one connection, all these connections follow the same path, which is a common practice in standard WDM networks. For each path-transmission tuple pair (p, t) we calculate the number of connections $W_{p,t}$, the number of transponders $N_{p,t}$, the cost of the transponders $C_{p,t}$, and the amount of spectrum $S_{p,t}$ (in spectrum slots) required to serve the demand. Depending on the type of network considered, transparent (no regenerators) or translucent (with regenerators), these calculations are as follows:

a) Transparent case:

For each path-transmission tuple pair (p, t) satisfying the transmission distance constraint (i.e., tuple t has higher reach distance l_t than the length of path p), we have the following two cases:

a.1) If $\Lambda_{sd} \le r_t$, a single flexpath is used for serving the (s, d) demand. The number of connections and the number of transponders are $W_{p,t} = N_{p,t} = 1$, the cost is $C_{p,t} = c_t$, and the number of spectrum slots used is $S_{p,t} = b_t$.

a.2) If $\Lambda_{sd} > r_t$, we break the requested demand Λ_{sd} into a number $\lfloor \Lambda_{sd}/r_t \rfloor$ of r_t-rate flexpaths and the remaining $\Lambda_{sd} - \lfloor \Lambda_{sd}/r_t \rfloor \cdot r_t$ demand is served using tuple $t_{\text{rem}}(p, t)$. Tuple t_{rem} is selected, from the tuples that can be transmitted over path p, as the one that minimizes the spectrum to transfer the remaining demand. Note that tuple t_{rem} is unique for a specific path-transmission tuple pair (p, t) and thus it is considered part of the (p, t) definition. So, we have

$$W_{p,t} = N_{p,t} = \left\lceil \frac{\Lambda_{sd}}{r_t} \right\rceil.$$

The above calculation includes the number of connections and transponders that use tuple t in addition to the one that uses tuple t_{rem}. Also,

$$C_{p,t} = \left\lfloor \frac{\Lambda_{sd}}{r_t} \right\rfloor \cdot c_t + c_{t_{\text{rem}}},\ S_{p,t} = \left\lfloor \frac{\Lambda_{sd}}{r_t} \right\rfloor \cdot b_t + b_{t_{\text{rem}}},$$

where c_t and $c_{t_{\text{rem}}}$ are the costs, and b_t and $b_{t_{\text{rem}}}$ are the spectrum slots, corresponding to tuples t and t_{rem}, respectively.

b) Translucent case:

For a translucent network, acceptable tuples for path $p \in P_{sd}$ are those with reach higher than the maximum link length of p. For each acceptable path-transmission tuple pair (p, t), the path p is swept from left to right and a regenerator is placed whenever required, that is, at the last node before the transmission distance l_t of the tuple is reached. Thus, for path-transmission tuple pair (p, t) we find the set of nodes where regenerators have to be placed to make the transmission feasible. With the placement of regenerators a *translucent* connection over path p is broken into subpaths, each corresponding to a *transparent* flexpath. Let $R_{p,t}$ be the set of subpaths that comprise the translucent connection. If no regenerators are used, the set $R_{p,t}$ contains only one element (the initial path p); otherwise, it contains paths $m_1, m_2, \ldots, m_{|R(p,t)|}$, the first of which starts at the source node s and ends at an intermediate regeneration node, the second starts at the previous regeneration node and ends at the destination or the next regeneration node, and so on, until destination d is reached. For each path-transmission tuple pair (p, t), the number of connections is defined as the number of end-to-end translucent connections that have to be established, while the number of transponders is defined so as to include the source transponders and the regenerators required to make these connections feasible, assuming that each regeneration is implemented by a transponder connected back-to-back. The number of transponders is thus equal to the number of flexpaths that are established. The calculations can be modified in a straightforward way to include the case in which the cost of regenerators is not equal to the cost of the transponders. In particular, we have the following cases:

b.1) If $\Lambda_{sd} \le r_t$, we use one translucent connection that consists of the transparent flexpaths defined in the set $R_{p,t}$. Thus, we have $W_{p,t} = 1$, $N_{p,t} = |R_{p,t}|$, $C_{p,t} = |R_{p,t}| \cdot c_t$ and $S_{p,t} = b_t$.

b.2) $\Lambda_{sd} > r_t$, we break the requested capacity Λ_{sd} into $\lfloor \Lambda_{sd}/r_t \rfloor$ connections, each of rate r_t, and the remaining $\Lambda_{sd} - \lfloor \Lambda_{sd}/r_t \rfloor \cdot r_t$ demand is served using tuple $t_{\text{rem}}(p, t)$, as in the transparent case. We have

$$W_{p,t} = \left\lceil \frac{\Lambda_{sd}}{r_t} \right\rceil N_{p,t} = \left(\left\lfloor \frac{\Lambda_{sd}}{r_t} \right\rfloor \cdot |R_{p,t}| \right) + |R_{p,t_{\text{rem}}}|,$$

where we note that a translucent connection consists of $|R_{p,t}|$ segments for tuple t and $|R_{p,t_{\text{rem}}}|$ segments for tuple t_{rem}, with each segment corresponding to a transparent flexpath. Also, we have

$$C_{p,t} = \left(\left\lfloor \frac{\Lambda_{sd}}{r_t} \right\rfloor \cdot |R_{p,t}| \right) \cdot c_t + |R_{p,t_{\text{rem}}}| \cdot c_{t_{\text{rem}}},$$

$$S_{p,t} = \left\lfloor \frac{\Lambda_{sd}}{c_t} \right\rfloor \cdot b_t + b_{t_{\text{rem}}}$$

Using the above formulas, we compute for each candidate path-transmission tuple pair (p, t) the number of connections $W_{p,t}$, the number of transponders $N_{p,t}$, the cost of the transponders $C_{p,t}$, and the spectrum (in spectrum slots) $S_{p,t}$ required to serve the demand. In the transparent network setting, a transmission using path-transmission tuple pair (p, t) is realized by one or more connections (p, t, i), $i \in \{1, 2, \ldots, W_{p,t}\}$, which correspond to flexpaths. For each candidate path-transmission tuple pair (p, t) in the translucent network setting we also store the set of transparent subpaths $R_{p,t}$ that comprise an end-to-end translucent connection. Thus, in the translucent network setting, a transmission using (p,t) is realized by one or more translucent connections, each comprising one or a sequence of transparent flexpaths (p,m,t,i), $i \in \{1,2,\ldots,W_{p,t}\}$ and $m \in R_{p,t}$. Note that the definition of the translucent connection includes as a subcase the transparent connection (when no regenerators are used and $R_{p,t} = p$). Thus, both transparent and translucent connections can be established in a translucent network. Figure 4 presents an example of the way the translucent connections are indexed.

The planning problem can be made easier by removing candidate path-transmission tuple pairs that will never be used in the solution. For a specific path p, suppose there is a tuple t that uses spectrum $S_{p,t}$, which is less than the spectrum $S_{p,t'}$ used by tuple t', and the transponders' cost $C_{p,t}$ is also less than the cost $C_{p,t'}$ of t'. Clearly, path-transmission tuple pair (p,t') cannot be part of the optimal solution, because we could always improve a solution containing t' by replacing t' with t. This is because our objective is to minimize a function of the maximum spectrum used and the transponders' cost and it is natural to assume that this function is monotonically increasing with respect to each of these two parameters.

More formally, we will say that path-transmission tuple pair (p,t) dominates path-transmission tuple pair (p,t'), denoted as $(p,t) > (p,t')$, if the following holds:

$$(p,t) > (p,t') \quad \text{iff} \quad C_{p,t} \le C_{p,t'} \quad \text{and} \quad S_{p,t} \le S_{p,t'}.$$

Dominated path-transmission tuple pairs are removed from the candidate solution space, since they will never be selected, reducing the solution space in a safe way (so as not to discard good solutions), along with the execution time of the algorithms.

Based on the above domination relation, we calculate for each demand (s,d) and for each of its candidate paths $p \in P_{sd}$ the set of Pareto optimal (nondominated) path-transmission tuple pairs Q_p. The set $Q_{sd} = \cup_{p \in P_{sd}} Q_p$ includes the path-transmission tuple pairs that are the candidate solutions to serve demand (s,d). It is the role of the RSA algorithm, to be described next, to choose one of these for serving demand (s,d). Since the number of connections, the number of transponders, and the number of spectrum slots are different for the transparent and translucent networks, we obtain different sets of nondominated path-transmission tuple pairs for these different types of networks.

1) Simplification Assumptions and Optimality of Solution: In the preprocessing phase described above the demands are broken into equal rate connections except for the remainder part that uses tuple t_{rem}. This approach yields the minimum number of transponders, but optimizing the spectrum utilization might require the breaking of demands into unequally sized connections, so as to satisfy more easily the spectrum continuity constraint. Algorithms where all combinations of connection splittings are precalculated can also be devised, but we decided to make the aforementioned assumption to obtain simpler algorithms and keep the number of variables as low as possible.

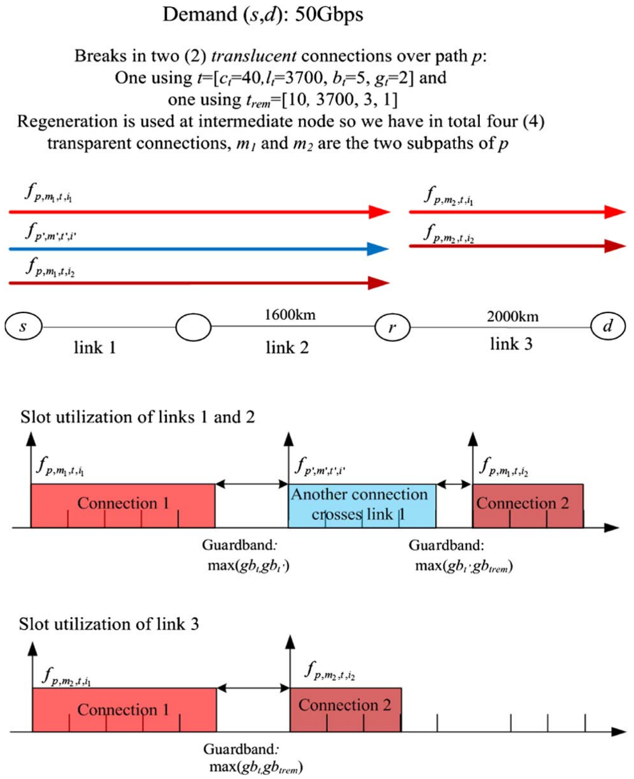

Fig. 4. Example of serving demand (s,d) using regenerators. The demand of 50 Gbps is served by path-transmission tuple (p,t) and is broken into two translucent connections, which are all regenerated at node r. The subpaths m_1 (starting at s and ending at r) and m_2 (starting at r and ending at d) form the set $R_{p,t}$ that comprise the subpaths of p. Thus, four transparent flexpaths are used in total, indexed as (p,m,t,i), where $m = m_1, m_2$ and $i = i_1, i_2$. The utilization of the spectrum of the links comprising path p is also presented. Another connection (blue) is served over the first two links, but since regeneration is performed at node r the spectrum used by (p,m_1,t,i_2) and (p,m_2,t,i_2) can change at r.

Moreover, in the translucent case the regeneration nodes of each path-transmission tuple pair are precalculated and included in the input passed to the algorithm. The regeneration placement choice we adopt minimizes the cost, but since regenerators can also function as spectrum converters (similar to wavelength converters in WDM networks), there may be cases where optimal spectrum usage is obtained for regeneration nodes different than the precalculated ones. A different formulation based on flow variables, or the same formulation but precalculating the path-transmission tuple pairs for all regeneration options could guarantee the finding of the optimal solution, but would be very complicated and most probably computationally intractable even for small-sized problems.

Note that in both cases the potential loss of optimality is related to the spectrum usage, but we ensure the finding of the optimal transponders' cost. So we argue that this assumption is very helpful in keeping computation time tractable, without appreciably deteriorating the performance of the algorithm; alternate models need to be considered only when spectrum utilization is the dominant optimization metric and demands are very bulky, so that they can be broken into many subconnections.

B. ILP Algorithms

In this section we present, for the sake of brevity, only the ILP formulation for the planning problem in translucent networks, since the formulation for transparent networks is similar (and easier). One difference between the two formulations is in the sets of nondominated path-transmission tuple pairs Q_{sd} that form the input, which are different in the transparent and the translucent case (see Subsection IV.A). Also, the input in the translucent network includes the sets $R_{p,t}$ of the transparent subpaths comprising an end-to-end translucent connection for each path-transmission tuple pair (p,t). So another difference is that the starting frequency ordering constraints and the related nonoverlapping spectrum assignment constraints have to be written for each transparent subpath m in the translucent network case, as opposed to only once for the whole path in the transparent network case.

Inputs:

Λ: Traffic matrix, Λ_{sd} corresponds to demand (s,d).

P_{sd}: Set of alternative paths for demand (s,d).

Q_{sd}: Set of nondominated path-transmission tuple pairs for demand (s,d) assuming a translucent network setting.

$C_{p,t}$: Cost of transponders required to serve demand (s,d) using path $p \in P_{sd}$ and tuple $t \in T$, that is, using path-transmission tuple pair (p,t).

$W_{p,t}$: Number of (translucent) connections required to serve demand (s,d) using path $p \in P_{sd}$ and tuple $t \in T$, that is, using path-transmission tuple pair (p,t).

$b_{p,t,i}$: Number of spectrum slots required for data transmission without guardband for connection (p,t,i) [connection $i \in \{1,2,\ldots,W_{p,t}\}$ of path-transmission tuple pair (p,t)]. In particular, if $W_{p,t}=1$, then $b_{p,t,i}=b_t$, and if $W_{p,t}>1$, then $b_{p,t,i}=b_t$ for $i \in \{1,2,\ldots,W_{p,t}-1\}$ and $b_{p,t,i}=b_{t_{\text{rem}}}$ for $i=W_{p,t}$.

$g_{p,t,i}$: Number of guardband spectrum slots required for the data transmission for connection (p,t,i). In particular, if $W_{p,t}=1$, then $g_{p,t,i}=g_t$, and if $W_{p,t}>1$, then $g_{p,t,i}=g_t$ for $i \in \{1,2,\ldots,W_{p,t}-1\}$ and $b_{p,t,i}=g_{t_{\text{rem}}}$ for $i=W_{p,t}$.

F_{total}: Upper bound on the number of spectrum slots required for serving all connections, set to

$$F_{\text{total}} = \sum_{sd} \max_{(p,t)\in Q_{sd}} \left(\sum_{i\in[1,\ldots,W_{p,t}]} (g_{p,t,i}+b_{p,t,i}) \right) = \sum_{sd} \max_{(p,t)\in Q_{sd}} (S_{p,t}).$$

w: Objective weighting coefficient, taking values between 0 and 1. Setting $w=0$ (or $w=1$) minimizes solely the cost of transponders used (or the maximum spectrum used, respectively).

Variables:

$x_{p,t}$: Boolean variable, equal to 1 if path-transmission tuple pair $(p,t)\in Q_{sd}$ is used to serve demand (s,d) and equal to 0 otherwise.

$f_{p,m,t,i}$: Integer variable that denotes the starting spectrum slot for transparent flexpath (p,m,t,i) [flexpath over subpath $m \in R_{p,t}$ of translucent connection $i \in \{1,2,\ldots,W_{p,t}\}$ of path-transmission tuple pair (p,t)]. If path-transmission tuple pair (p,t) is not utilized to serve (s,d), then variable $f_{p,m,t,i}$ does not affect the solution. Note that $f_{p,m,t,i} < F_{\text{total}}$.

$\delta_{p,m,t,i,p',m',t',i'}$: Boolean variable that equals 0 if the starting frequency $f_{p,m,t,i}$ for transparent flexpath (p,m,t,i) is smaller than the starting frequency $f_{p',m',t',i'}$ for flexpath (p',m',t',i'), i.e., $f_{p,m,t,i} < f_{p',m',t',i'}$. Variable $\delta_{p,m,t,i,p',m',t',i'}$ is defined only if subpaths $m \in R_{p,t}$ and $m' \in R_{p',t'}$ share a common link.

S: Highest spectrum slot used.

C: Cost of utilized transponders.

ILP formulation

$$\text{Minimize } w\cdot S + (1-w)\cdot C$$

Subject to the following constraints:

- *Cost function definition:*

For all (s,d) pairs, all $(p,t)\in Q_{sd}$, all $i \in \{1,2,\ldots,W_{p,t}\}$, and all $m \in R_{p,t}$,

$$S \ge f_{p,m,t,i} + b_{p,t,i}, \tag{1}$$

$$C = \sum_{sd} \sum_{(p,t)\in Q_{sd}} C_{p,t}\cdot x_{p,t}. \tag{2}$$

- *Path-transmission tuple pair selection:*

For all (s,d) pairs,

$$\sum_{(p,t)\in Q_{sd}} x_{p,t} = 1. \tag{3}$$

- *Starting frequencies ordering and nonoverlapping spectrum constraints:*

For all (s,d), all $(p,t)\in Q_{sd}$, all $m \in R_{p,t}$, all $i \in \{1,2,\ldots,W_{p,t}\}$, all (s',d'), all $(p',t')\in Q_{s'd}$, all $m' \in R_{p',t'}$, where m and m' share at least one common link, and all $i' \in \{1,2,\ldots,W_{p',t'}\}$,

$$\delta_{p,m,t,i,p',m',t',i'} + \delta_{p',m',t',i',p,m,t,i} = 1, \tag{4}$$

$$f_{p',m',t',i'} - f_{p,m,t,i} \le F_{\text{total}}\cdot \delta_{p,m,t,i,p',m',t',i'}, \tag{5}$$

$$f_{p,m,t,i} - f_{p',m',t',i'} \le F_{\text{total}}\cdot \delta_{p',m',t',i',p,m,t,i}, \tag{6}$$

$$f_{p,m,t,i} - (b_{p,t,i} + \max(g_{p,t,i}, g_{p',t',i})) - f_{p',m',t',i'} \le (F_{\text{total}} + \max(g_{p,t,i}, g_{p',t',i'}))\cdot(1-\delta_{p,m,t,i,p',m',t',i'} + 2 - x_{p,t} - x_{p',t'}), \tag{7}$$

$$f_{p',m',t',i'} - (b_{p',t',i'} + \max(g_{p,t,i}, g_{p',t',i'})) - f_{p,m,t,i} \le (F_{\text{total}} + \max(g_{p,t,i}, g_{p',t',i'}))\cdot(1-\delta_{p',m',t',i',p,m,t,i} + 2 - x_{p',t'} - x_{p,t}). \tag{8}$$

Constraints (4)–(6) ensure that either $\delta_{p,m,t,i,p',m',t',i'} = 1$ or $\delta_{p',m',t',i',p,m,t,i} = 1$, according to the ordering of the starting frequencies $f_{p,m,t,i}$ and $f_{p',m',t',i'}$. Note that since the starting frequencies $f_{p,m,t,i}$ and $f_{p',m',t',i'}$ are bounded by constant F_{total} their difference is also bounded by that constant. Also note that for the path-transmission tuple pairs that are not utilized ($x_{p,t} = 0$ or $x_{p',t'} = 0$), the ordering of their starting frequencies does not play a role (see also the next set of constraints). When one (or both) of the path-transmission tuple pairs (p,t) and (p',t') is not selected ($x_{p,t} = 0$ or $x_{p',t'} = 0$), then we do not have to consider the overlapping of their transparent flexpaths. In this case, Constraints (7) and (8) are deactivated (meaning that they are satisfied for all values of $f_{p,m,t,i}$ and $f_{p',m',t',i'}$), since the right-hand side of the constraints takes a value larger than F_{total}, which is always higher than the left-hand side. When both path-transmission tuple pairs are utilized ($x_{p,t} = 1$ and $x_{p',t'} = 1$), one of Constraints (7) or (8) is activated according to the values of the related δ variables (ordering in the spectrum domain). In this case, Constraints (7) and (8) enforce the nonoverlapping spectrum allocation to the flexpaths used by the connections.

The above ILP formulation finds the path-transmission tuple pair (p,t) (recognized by $x_{p,t} = 1$) to serve each demand. This includes the choice of the BVT configuration to be used for the connections. It also finds the starting frequencies $f_{p,m,t,i}$ of the transparent flexpaths to be established for serving the demand. The objective is to minimize a weighted sum of the maximum spectrum and the cost of transponders (number and type) used. The weighting coefficient w controls the relative significance given to these two cost parameters in the optimization function. Values of w close to 0 make the transponders' cost the dominant optimization parameter, in which case transponder configurations that have high reach and rate and low cost are chosen, neglecting their spectrum efficiency. In contrast, values of w close to 1 make the spectrum used the dominant optimization parameter, in which case a large number of transponders may be utilized, and the effort is placed on choosing tuples with high spectral efficiency and packing the flexpaths in the spectrum domain as much as possible to save on the spectrum used.

C. Heuristic Algorithm

We now present the heuristic algorithms for planning flexible transparent and translucent networks. We have extended the algorithm of [8] to take as input the feasible transmission options described by the (reach, rate, spectrum, guardband, cost) tuples, establish multiple connections for demands and also cater for translucent connections.

The proposed heuristics sequentially serve demands one-by-one, in a particular order. We keep track of the link spectrum utilizations, updating them upon serving each demand, so that the demands served are affected by the previously made choices. Thus, the ordering in which the demands are served plays an important role in the performance. We use the simulated annealing (SimAn) meta-heuristic to search among different orderings and find better solutions. Two different versions of the algorithm were devised, for transparent and translucent networks, which mainly differ in the input they receive. We will describe both of them as a single algorithm, commenting on their differences when deemed appropriate.

The spectrum utilization of a link is represented by a three state vector, called the link slot utilization vector, of length equal to F_{total}. A spectrum slot can be in one of the following states: i) free (denoted by state u_f), ii) used for data transmission (denoted by u_d), or iii) used as a guardband (denoted by u_g). The rules are that data slots cannot be used by new flexpaths, free slots can be used for data, while free and guardband slots can be used for guardband by new flexpaths. To enforce these rules, we calculate the slot utilization vector of a path using an (associative) 3-ary operator for combining ("adding") the spectrum slots of the links that comprise it, defined as follows:

$$u_f \oplus u_d = u_d, u_f \oplus u_g = u_g, u_f \oplus u_f = u_f, u_g \oplus u_g = u_g,$$
$$u_d \oplus u_d = u_d, u_d \oplus u_g = \oplus u_d. \tag{9}$$

To serve a flexpath over a path using tuple $t = (l_t, r_t, b_t, g_t, c_t)$ requesting a specific number b_t of data spectrum slots and g_t guardband slots, we have to find b_t contiguous free (in state u_f) slots, and these slots need to have from each side g_t contiguous free or guardband (in state u_f or u_g) slots in the path utilization vector. Note that we allow already assigned guardband slots to be present at the spectrum edges of a new flexpath, thus enabling the reuse of these slots for a guardband, a feature that is useful when flexpaths require different amounts of guardband.

The sequential heuristic algorithm works as follows. We are given the traffic matrix Λ and the tuple lookup table T that consists of the candidate transponder configurations. We perform the preprocessing phase described in Subsection IV.A to calculate for each demand (s,d) the set Q_{sd} of candidate nondominated path-transmission tuple pairs (p,t) to serve it. We start with an empty network, where all link utilization vectors have initialized with u_f values for the slot states. We keep track of the cost C of utilized transponders and the maximum number S of slots that are utilized up to a point. We initialize $C = S = 0$. We start serving the demands according to the ordering. For a demand (s,d) we examine all candidate path-transmission tuple pairs (p,t) in Q_{sd}. For a path-transmission tuple pair (p,t) we create temporary link slot utilization vectors for all links. Then for each of the connections $\{1, 2, \ldots, W_{p,t}\}$ that have to be established over path-transmission tuple pair (p,t) (or for each transparent flexpath $m \in R_{p,t}$, if we consider a translucent network), we find free spectrum space to accommodate the flexpath (p,t,i) [or (p,m,t,i), respectively, for translucent networks]. To do so we compute the temporary utilization vector of path p (or subpath m in translucent networks), by adding the temporary utilization vectors of the links that comprise it, using the relationships described in Eq. (9), and then we scan the temporary utilization vector of the path from left to right to find the first placement that can serve the flexpath. The spectrum continuity constraint is enforced across a path by the definition of the slot addition among the links. We then update the temporary slot utilization vectors of the links. After establishing all flexpaths of the path-transmission tuple pair (p,t) we calculate, using the temporary link utilization vectors, the temporary transponders' cost $\tilde{C}_{p,t}$ and the maximum slots $\tilde{S}_{p,t}$. We then move to examine the next path-transmission tuple pair in Q_{sd}, define new temporary utilization vectors, calculate the slots and cost, and so on. Branch-and-bound types of techniques (stop examining path-transmission tuple pairs that have worse performance than the best found up to that point) speed up the searching process. After doing this for all candidate path-transmission tuple pairs $(p,t) \in Q_{sd}$ we select the one that minimizes the objective, and, in particular, the path-transmission tuple pair that is given by

$$\arg \min_{(p,t)\in Q_{sd}} (w \cdot \tilde{S}_{p,t} + (1-w) \cdot \tilde{C}_{p,t}).$$

After selecting the path-transmission tuple pair to serve demand (s,d), we update the utilization vectors of the links (the original vectors, not the temporary ones) and move to serve the next demand. The algorithm finishes when it has served all demands, returning the final values of C, S, and the objective cost.

Since the performance of the algorithm depends on the ordering of demands used, we use the SimAn meta-heuristic to find good orderings, in a manner similar to that used in [8]. Neighboring orderings are defined by interchanging two demands randomly chosen from a uniform distribution. The sequential heuristic runs for a specific ordering and calculates the objective cost. The standard SimAn process using the number of iterations as the stop criterion is employed. The solution that yields the lowest objective is finally selected.

For a given ordering the heuristic algorithm examines all the nondominated path-transmission tuple pairs, and in the worst case it finds for each connection of each path-transmission tuple pair a valid spectrum assignment by manipulating the link and path utilization vectors. The number of operations performed depends linearly on the number of nondominated path-transmission tuple pairs, the number of connections to be established, the number of links, and the size of the utilization vectors, and thus the proposed heuristic is polynomial to the size of the input. Simulated annealing is used to search among different orderings, remaining polynomial and being able to trade-off performance for running time by controlling the number of iterations (different orderings that are examined).

V. Performance Results

To evaluate the performance of the proposed algorithms and also quantify the benefits that can be obtained by utilizing a flexible optical network as opposed to a fixed-grid one we conducted a number of simulation experiments. The size of the spectrum slots was taken to be $F = 6.25$ GHz. We assumed the use of a single type of flexible OFDM transponder that supports transmissions of up to 50 GHz and modulates up to 64 QAM, so as to transmit up to 600 Gbps. The (reach, rate, spectrum, guardband, cost) tuples used as input to these experiments were obtained from studies on physical layer impairments for optical OFDM networks [11]. Figures 1 and 2 show the function of the transmission reach we used for defining the feasible tuples of the transponder. We set the cost parameter in the transmission tuples equal to a constant (e.g., 5.5). Since we assumed a single type of BVT, the transponders' cost in the flexible network is linear to the number of BVTs used.

A. *Optimality Performance of the Heuristics*

We start by examining the optimality performance of the heuristic algorithms for transparent and translucent networks by comparing their performance to that of the ILP algorithms in small scale experiments.

We used Matlab to implement the heuristic IA-RSA algorithm, IBM ILOG CPLEX [24] for ILP solving, and Matlab's built-in SimAn meta-heuristic. In this set of experiments we used $k = 2$ candidate paths for each source–destination pair, to keep the number of variables and constraints of the ILP algorithms low.

Subsection V.A.1 presents the results for the transparent case, while Subsection V.A.2 presents the results for the translucent case. We report results for the ILP algorithms (stopped after running for 1.45 h) and also for the heuristic algorithms using the SimAn meta-heuristic with 10, 100, and 1000 iterations. We performed these experiments assuming the six-node network topology shown in Fig. 5. We used two different variations of the network, one with the link lengths shown in Fig. 5 and one with double these link lengths. Regarding the traffic, we created traffic matrices for average loads per source–destination pair ranging from 10 to 500 Gbps. For each load we created five traffic matrices, by selecting the requested capacity for each source-destination pair (s,d) according to an exponential distribution with mean the given average traffic load. Results are averaged for each load over the five created traffic matrices. The performance metrics we used for the comparisons were the average number of BVTs used (the cost is linear to this metric), the average number of the highest spectrum slots used, and the average running time in seconds.

We executed the algorithms for values of the weighting coefficient in the optimization function equal to $w = 0.01$ and $w = 1$. When setting $w = 0.01$ the algorithms optimize the number (cost) of utilized transponders, while when setting $w = 1$ the algorithms optimize solely the maximum spectrum used. We avoided using $w = 0$, since this simplifies the problem and removes its combinatorial nature: the algorithms select for each demand the path-transmission tuple pair with the lowest number of transponders irrespective of the other demands and spectrum allocation is done by just satisfying the non-overlapping assignment constraint.

1) Transparent Network Experiments: In this subsection we examine the performance of the IA-RSA algorithms for transparent networks. Table I presents the results obtained with weighting coefficient $w = 1$, where the objective is to minimize the maximum spectrum used, for the initial and double link lengths.

The transparent IA-RSA ILP algorithm was able to track optimal solutions for average network loads up to 100 Gbps for the initial and the double link length cases, as indicated by the average running time, which for these cases was 6300 s (recall that the ILP algorithm was stopped after running for 1.45 h for each experiment). So, for higher loads we are not sure if the ILP algorithm found the optimal solutions. As the load increases the number of connections that need to be established increases, since each demand is broken into multiple connections, thus increasing the number of ILP variables, and making the problems intractable. Even in the light traffic load cases where the ILP algorithm found optimal solutions, its average running time was very high, of the order of thousands of seconds.

The performance of the proposed SimAn heuristic was very good, as it was able to serve all the demands using a maximum spectrum that is close to that found by the ILP algorithm, for the light loads where the ILP was able to track the optimal solutions. For heavy loads the SimAn heuristic even managed to find better solutions than the ILP algorithm (of course, in these cases, the ILP had to be stopped). Naturally, as the number of SimAn iterations increases, the algorithm's performance improves (the maximum spectrum required to serve the demands decreases), but its running time increases. However, as the running time of SimAn is polynomial to the input size, it will remain acceptable for networks larger than the one examined here. Moreover, the running time of the algorithm is controlled by the number of SimAn iterations, enabling us to trade-off running time for performance. The results, at least for this small network, show that even a few SimAn iterations (e.g., 100) are sufficient to obtain close to optimal performance with low running times.

For average load of 10 Gbps per (s, d) demand, a single connection per demand is established (30 transponders for 30 demands), but as the load increases the transponders reach their limits and multiple transponders/connections are used to serve a demand. This also affects the spectrum used, which increases with load, not only because more spectrum is needed to support the increased demands, but also because the number of connections established increases, and the spectrum continuity constraint reduces the efficiency of the network due to spectrum fragmentation.

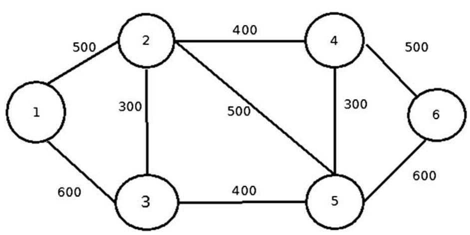

Fig. 5. Small network topology and link lengths in kilometers.

By comparing the results for single and double link lengths we observe that the average spectrum and number of transponders utilized in the network with double link lengths are higher than those in the initial network, especially at heavy load. This is because doubling the link lengths reduces the feasible candidate path-transmission tuple pairs, since only tuples with reach higher than the path lengths can be candidate solutions in a transparent network. Modulation formats with fewer bits per symbol are supported over the longer paths, meaning that lower spectral efficiency connections are utilized. Thus, more spectrum and more connections are needed to serve the same traffic, and the effect becomes more pronounced with increasing load. For small average network load (10 Gbps), both networks have similar performance since all demands are served by single connections. As load increases, the connections (transponders) for both algorithms increase, but in the double link length network the number of utilized connections and the utilized spectrum increases more rapidly since the demands use lower spectral efficiency tuples. Note that, although the number of candidate path-transmission tuple pairs is reduced in the double link length case, the running time of the algorithms and particularly that of the ILP algorithm is increased. This has to do again with the lower spectral efficiency of the solutions (tuples used) in the double link length case, which requires more connections to be established and thus a higher number of ILP variables. This complicates vastly the solution of the ILP formulation, especially when considering spectrum optimization (weighting coefficient $w = 1$) that involves many variables and constraints. Note that for average load 500 Gbps with the initial link lengths, and for loads higher than 300 Gbps with the double link lengths, the solutions found by the SimAn heuristic are better than those found by the ILP algorithm. The performance deterioration of the ILP algorithm becomes evident earlier for double link lengths, due to the higher number of variables used.

Table II presents the results obtained when the weighting coefficient in the objective function is chosen to be $w = 0.01$, for the initial and the double link length cases. This value for w makes the algorithms minimize primarily the number (cost) of transponders used and secondly the spectrum used. As stated earlier, we chose not to use $w = 0$, because such a choice would vastly simplify the problem. In that case the problem would lose its combinatorial nature and could be solved optimally by applying a simple heuristic to each demand separately. This was verified by running the CPLEX ILP algorithm for $w = 0$, and observing that it finished within a few seconds returning solutions that had always exactly the same number of transponders as the heuristic algorithm. Note that, in this study, we assume a single model of BVT. Having available BVT with different capabilities and costs would make the transponder cost minimization problem more difficult.

From Table II we observe the near-optimal performance of the heuristic algorithm as is evident by comparing it to the ILP algorithm. In particular, for both network cases the heuristic algorithm was able to find solutions with exactly the same number of transponders and almost the same required spectrum as the ILP algorithm, even with 10 iterations, in all experiments. Optimizing the spectrum used (experiment reported in Table I) is much harder than optimizing transponders' usage for a single type of transponder (examined here). In the results of Table II, although we are not sure that the ILP algorithm has found the optimal solutions for heavy loads, the solutions found by the heuristic algorithm used exactly the same number of transponders (main objective) and more spectrum (secondary objective) in the majority of cases. The heuristic outperforms the ILP algorithm in maximum used spectrum only for double link lengths and average loads higher than 300 Gbps. This outperformance of the ILP by the SimAn algorithm will eventually happen, at higher loads than those examined, for the initial link lengths network, as well. We expect, however, that even at higher loads the number of transponders used by the heuristic and the ILP algorithm will be similar, since meeting this objective is relatively easy.

By comparing Tables I and II we can see the difference in the maximum spectrum used and the number of transponders at the two extreme cases, $w = 1$ and $w = 0.01$, each of which minimizes one of the two objectives of interest. To reduce the utilized spectrum ($w = 1$) a larger number than the minimum number of transponders is used, indicating that some of these transponders use transmission tuples with higher modulation format (more bits/symbol) that transmit at a lower total rate. On the other hand, minimizing the utilized transponders ($w = 0.01$) selects tuples with the maximum total rate that might not use the higher possible modulation format. Searching for solutions that optimize both the spectrum and the number of transponders, using values for the weighting coefficient between the two extremes ($0 < w < 1$), would yield spectrum and transponder performance in between the minimum values that are reported in these tables.

2) Translucent Network Experiments: In this subsection, we evaluate the performance of the versions of the ILP and heuristic algorithms designed for planning translucent networks. We used the same network and traffic to obtain a better understanding of the key differences between the transparent and the translucent network settings. The transparent network is a special case of the translucent network in which no regenerators are employed. Serving demands transparently tends to result in the lowest possible number (cost) of transponders. However, since the set of candidate path-transmission tuple pairs that are passed to the translucent algorithm includes these transparent options, the translucent algorithm can choose to establish transparent connections if these are the ones that optimize the objective. Thus, the optimal performance of the translucent network will always be better than that of the transparent network.

Table III presents the results obtained when the objective is the minimization of the maximum spectrum used ($w = 1$). Regeneration relaxes the spectrum continuity constraint, since regenerators can also perform spectrum translation, similar to wavelength converters in standard WDM systems. Thus, by comparing the results of Tables III and I we can quantify the spectrum improvements obtained when designing the network in a translucent manner. These improvements in spectrum come at the cost of a higher number of transponders used for establishing the translucent, as opposed to the transparent, connections for the initial network link lengths, but the number of transponders does not contribute to the optimization cost in this set of experiments ($w = 1$). In the double link length network, translucent connections enable the use of higher spectral efficiency tuples. These are tuples with high modulation formats but low reach that need regeneration to be established over the longer paths. Thus, the improvements obtained in the translucent over the transparent network case for double link lengths (bottom parts of Tables I and III) are more significant than those obtained for the initial link lengths (top parts of Tables I and III).

The performance of the heuristic algorithm for translucent networks is very close to that of the corresponding ILP algorithm. The heuristic for translucent networks is slower than the one for transparent networks, since the number of path-transmission tuple pairs that are available and are examined is higher due to the use of regenerators. Still the running time is acceptable, when compared to the ILP algorithm that exhibits scaling problems both with respect to the size of network and the load. Finally, note that the translucent heuristic algorithm outperforms the

TABLE I
PERFORMANCE OF THE SIX-NODE NETWORK ASSUMING A TRANSPARENT NETWORK SETTING AND $w = 1$ (SPECTRUM OPTIMIZATION)

Network	Load (Gbps)	ILP Av. Spectr.	ILP Av. TR	ILP Av. Time	SimAn 10 Av. Spectr.	SimAn 10 Av. TR	SimAn 10 Av. Time	SimAn 100 Av. Spectr.	SimAn 100 Av. TR	SimAn 100 Av. Time	SimAn 1000 Av. Spectr.	SimAn 1000 Av. TR	SimAn 1000 Av. Time
Initial link lengths	10	19.4	30	1138.3	21.6	30	1.4	20.4	30	5.6	20	30	52.0
	100	52.6	32	1492.4	62.8	31.6	5.9	59	31.6	24.1	58.6	31.6	226.3
	300	139.6	42.6	6297.9	159	44.2	23.0	157.6	44	96.6	157.2	43.8	906.5
	500	265.2	59.2	6300	264.8	61	52.8	259	63.4	224.4	259	63.4	2141
Double link lengths	10	20.2	30.2	1198	22.8	30	1.3	21.8	30	6.1	21.8	30	51.9
	100	91.8	43	2239	101.6	41.6	6.8	98.4	42.2	27.1	95.4	42.8	250.2
	300	304.4	80.8	6300	278.6	91.4	28.3	271.8	91.8	123.5	269.8	91.2	1164.0
	500	566.2	143	6300	469.4	131.8	67.1	442.6	141.4	299.4	439.6	139.4	2857.1

TABLE II
PERFORMANCE OF THE SIX-NODE NETWORK ASSUMING A TRANSPARENT NETWORK SETTING AND $w = 0.01$ (TRANSPONDER COST OPTIMIZATION)

		ILP			SimAn 10			SimAn 100			SimAn 1000		
Network	Load (Gbps)	Av. Spectr.	Av. TR	Av. Time	Av. Spectr.	Av. TR	Av. Time	Av. Spectr.	Av. TR	Av. Time	Av. Spectr.	Av. TR	Av. Time
Initial link lengths	10	19.4	30	1204.4	22.2	30	1.5	21.6	30	5.6	20.6	30	53.2
	100	52.2	30.6	1208.4	63	30.6	6.0	61.8	30.6	23.8	60.4	30.6	226.3
	300	154.4	38.6	4281.9	178	38.6	23.3	175.6	38.6	95.2	174.4	38.6	908.9
	500	275.8	52.2	6300	304.6	52.2	52.3	304.4	52.2	223.6	304.4	52.2	2136.2
Double link lengths	10	20.2	30	1198	23.2	30	1.4	22.6	30	5.4	22	30	53.4
	100	102.8	37.6	2139	116.4	37.6	6.1	112.4	37.6	25.7	112.4	37.6	250.4
	300	351.4	68.6	6300	367.2	68.6	27.1	363	68.6	118.7	361.4	68.6	1145.4
	500	592.8	105.2	6300	588.6	105.4	65.4	588.4	105.4	290.4	585.6	105.4	2820.8

corresponding ILP algorithm for average load 500 Gbps for double link lengths, and this will happen at higher loads than those examined for initial link lengths. Considering that in the transparent algorithm this overtaking happens at lower loads, this indicates that the efficiency of the translucent heuristic is slightly worse than that of the transparent algorithm. This was expected due to the higher number of candidate solutions (candidate path-transmission tuple pairs) available in the translucent algorithm.

Table IV reports the results obtained for $w = 0.01$, where the primary objective is the minimization of the number (cost) of transponders used, and spectrum is only a secondary one. From these results, and similar to the results reported in Table II for transparent networks, we can verify that the proposed heuristic algorithm has superior performance when optimizing the number of transponders used, since in all cases it was able to find solutions that had the same cost as those found by the ILP algorithm and maximum spectrum used close to that needed by the ILP algorithm. As discussed in the transparent network case, optimizing the transponder usage is easier than the spectrum used problem.

When the objective is to minimize the number of transponders, then if the network has relatively small link distances, it can be planned transparently quite efficiently, as done in the previous subsection (Subsection V.A.1). Adding regenerators to a connection increases the number of transponders and opposes the specific objective cost. When all or almost all of the transmission tuples are available and high modulation format connections can be established and most demands utilize single connections, the translucent algorithm produces a transparent solution that has the minimum cost. This is verified in this set of experiments for the initial link lengths and for light to medium loads, by comparing the top parts of Tables II and IV, where we see that the spectrum and the number of transponders utilized are very close for the transparent and the translucent networks. In the double link length network, the candidate path-transmission tuple pairs are reduced and some highly spectral efficient tuples are not available in the transparent case. Adding regenerators, however, enables the use of these highly spectrally efficient tuples, resulting in a smaller number of transponders required to serve the same traffic, even if they use intermediate regenerators. This case appears at high traffic loads, where demands are broken into more than one connection. Thus, for heavy load and long paths, and probably contrary to what one would initially expect, the number of transponders can be reduced by establishing translucent connections as opposed to the transparent case.

B. Comparing a Flexible OFDM to a MLR WDM System

In this section we compare the performance of a flexible OFDM optical network to that of a fixed-grid MLR WDM

TABLE III
PERFORMANCE OF THE SIX-NODE NETWORK ASSUMING A TRANSLUCENT NETWORK SETTING AND $w = 1$ (SPECTRUM OPTIMIZATION)

		ILP			SimAn 10			SimAn 100			SimAn 1000		
Network	Load (Gbps)	Av. Spectr.	Av. TR	Av. Time	Av. Spectr.	Av. TR	Av. Time	Av. Spectr.	Av. TR	Av. Time	Av. Spectr.	Av. TR	Av. Time
Initial link lengths	10	19.4	30	1246	21.6	30	1.1	20.4	30	4.1	20	30	35.4
	100	42.8	38.8	1657	51.6	40.8	6.4	50.2	40	24.7	50.2	40	213.1
	300	124.2	50.8	6223	138.8	63.8	26.7	138.4	64.6	112.4	135.6	64.6	990.0
	500	221.2	69.2	6300	226.2	88.8	66.5	224.8	87.8	281.8	223.8	88.4	2573.3
Double link lengths	10	17.6	31.2	1434	21.2	31.4	1.2	20.4	31.4	4.9	20.4	31.4	32.6
	100	59.4	44	2351	67.2	48.2	9.2	65.8	46.4	35.2	64.8	47	263.7
	300	174.6	75.6	6300	179.8	82.2	35.7	179.8	82.2	148.1	179.8	82.2	1357.6
	500	340.8	107.8	6300	295.6	121.2	80.5	292.6	121.6	366.6	292.6	121.6	3311.4

TABLE IV
PERFORMANCE OF THE SIX-NODE NETWORK ASSUMING A TRANSLUCENT NETWORK SETTING AND $w = 0.01$ (TRANSPONDER COST OPTIMIZATION)

Network	Load (Gbps)	ILP Av. Spectr.	ILP Av. TR	ILP Av. Time	SimAn 10 Av. Spectr.	SimAn 10 Av. TR	SimAn 10 Av. Time	SimAn 100 Av. Spectr.	SimAn 100 Av. TR	SimAn 100 Av. Time	SimAn 1000 Av. Spectr.	SimAn 1000 Av. TR	SimAn 1000 Av. Time
Initial link lengths	10	19.4	30	1135	22.2	30	1.1	21.6	30	4.5	21	30	32.6
	100	50.6	30.6	1447	61.8	30.6	6.9	60.2	30.6	26.9	59.2	30.6	243.3
	300	147.4	38.6	2929	166.2	38.6	28.1	164.6	38.6	113.5	164.6	38.6	1093.3
	500	271	52.2	6300	299.2	52.2	64.5	298.4	52.2	289.8	298.4	52.2	2663.2
Double link lengths	10	20.2	30	1198	23.2	30	1.4	22.6	30	5.4	22	30	53.4
	100	102.8	37.6	2139	116.4	37.6	6.1	112.4	37.6	25.7	112.4	37.6	250.4
	300	351.4	68.6	6300	367.2	68.6	27.1	363	68.6	118.7	361.4	68.6	1145.4
	500	592.8	105.2	6300	588.6	105.4	65.4	588.4	105.4	290.4	585.6	105.4	2820.8

network. For planning the MLR WDM network we also used the translucent heuristic developed here, since it is general and can be applied to such networks as well, by defining appropriate (reach, rate, spectrum, guardband, cost) tuples, as discussed in Subsection III.A. In this comparison, we used only the algorithm for planning translucent networks, since transparent networks form a special case of translucent ones, and the translucent algorithm was shown to achieve better performance in the previous set of experiments. We assumed a MLR system that utilized four types of transponders with the following (reach, rate, spectrum, guardband, cost) characteristics: (3200 km, 10 Gbps, 50 GHz, 0, 1), (2300 km, 40 Gbps, 50 GHz, 0, 2.5), (2100 km, 100 Gbps, 50 GHz, 0, 3.75), and (790 km, 400 Gbps, 50 GHz, 0, 5.5) [15]. The unit cost is taken as the cost of a 10 Gbps transponder. The MLR system employs four transponders of different capabilities and costs, while we assumed that the flexible OFDM network has a single type but tunable transponder. In this section we assumed that the OFDM transponder has a maximum rate of 400 Gbps, as opposed to the 600 Gbps used in the previous experiments. For a fair comparison, we set the cost of the OFDM transponders (BVTs) to 5.5, so that both the OFDM and the 400 Gbps MLR transponders have the same maximum spectral efficiency and cost. We used the generic Deutsche Telekom (DT) network topology for the comparison [8], so that the results obtained are representative of real networks. We extrapolated future traffic demands for the DT network from 2012 until 2022, assuming that each year the traffic is uniformly increased by 34% (as observed to be the case for the past few years [1]). The average demand capacity for 2012 is 36.5 Gbps (max 115 Gbps) and 690 Gbps for 2022 (max 2145 Gbps).

Figures 6(a)–6(c) present the results obtained for the two types of networks, flexible OFDM and fixed-grid MLR, and for two different choices of the weighting coefficient in the objective function, namely, $w = 1$ (maximum spectrum used minimization) and $w = 0.01$ (transponders' cost minimization). In Fig. 6(a) we see that the flexible network uses much lower maximum spectrum than the MLR network. This was expected since in the flexible network the connections are established utilizing exactly the amount of spectrum they require, while in the MLR case they always utilize 50 GHz per wavelength and some connections utilize low spectral efficiency transponders (e.g., 10 or 40 Gbps transponders). The *MLR–optimize TR cost* case starts at the year 2012 using high spectrum, because it uses these low spectral efficiency but cheap transponders to serve the traffic (in this case we only optimize the transponders' cost). As the years and the load increase, the MLR network gradually starts employing more the higher spectral efficiency transponders when optimizing both the spectrum (for obvious reasons) and the transponders' cost. This is because, as traffic increases, it becomes more cost efficient to utilize a single high rate transponder than many low rate ones. As the load increases the maximum spectrum used in the *MLR–optimize TR cost* case decreases and then starts to increase again, since after a certain point (year 2018) almost all spectral inefficient transponders have been replaced by efficient ones. This is the reason that the performance of the *MLR–optimize TR cost* and *MLR–optimize spectrum* cases converge in both Figs. 6(a) and 6(c). With respect to the transponders cost [Fig. 6(c)], the *MLR-optimize TR cost* case achieves the best performance for light load (see above comments), but after year 2018, it becomes slightly worse than the *OFDM-optimize TR cost* case. At light load, all demands are served by single and transparent connections [according to Fig. 6(b), for year 2012 the number of transponders is equal to the number of demands]. As high rate demands appear, the algorithms utilize higher rate transponders (in the MLR network) or higher rate configuration tuples (in the flexible network) but also break some demands into multiple connections and start employing regenerators to enable the use of higher spectral efficiency connections. The finer granularity and the more transmission options of the BVT in the *OFDM-optimize spectrum* case can lead to gains in the transponders' cost, which is what we observe at heavy loads in Fig. 6(c).

The maximum spectrum used in the *flexible–optimize spectrum* and *flexible–optimize TR cost* cases is very similar at light load, but as the load increases the *optimize spectrum* case becomes significantly better. At light load almost all demands are served by single and transparent connections, and there are not many optimization options. With increasing load, the set of candidate solutions increases and the different optimization objectives result in totally

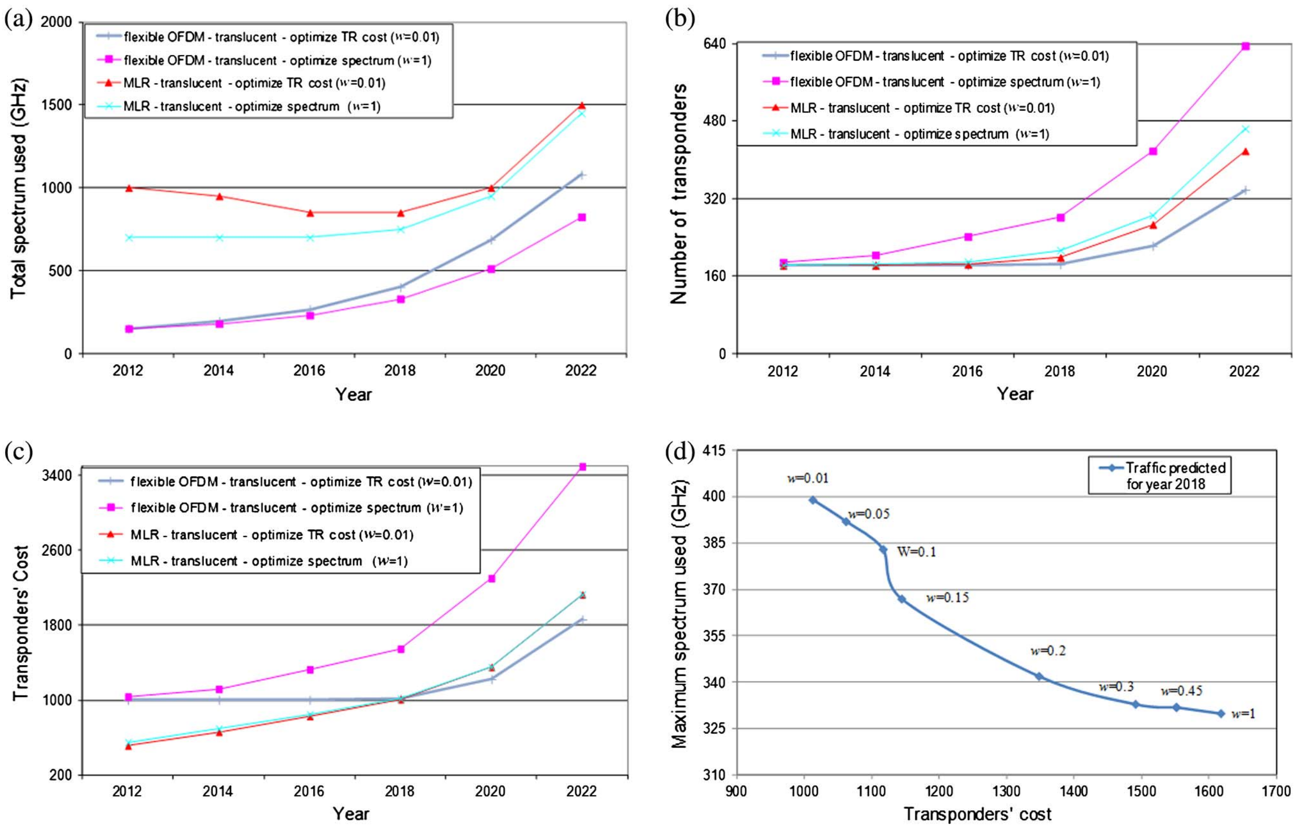

Fig. 6. (a) Maximum spectrum used (gigahertz), (b) number of transponders, and (c) transponders' cost, for the flexgrid OFDM and the MLR network, for optimizing the maximum spectrum used ($W = 1$) and the transponders' cost ($W = 0.01$) on the DT network. (d) Trade-off between maximum spectrum used and transponders' cost in the flexgrid network for year 2018.

different solutions, as observed in Figs. 6(a) and 6(c), where we see that at medium and heavy load there is a significant difference between the *flexible–optimize spectrum* and *flexible–optimize TR cost* cases when considering the spectrum used and the transponders cost. This is not the case in the MLR network, where beyond a certain load most demands are served with the 400 Gbps transponders.

The high cost of planning the flexible OFDM network at light load is due to the use of powerful but expensive transponders that are not fully utilized, a problem that would be ameliorated if more than one type of BVT with different performance/cost capabilities were used. However, from the operator's point of view, it might be better to place powerful and tunable transponders at an early stage, when these have reasonable prices, and tune them to serve the increased traffic demands at later years. In the MLR case, the cheap–low rate transponders have to be replaced later by more efficient ones. This is not accounted for here, since we do not study the incremental cost evolution of the network, but only the cost at a given point in time. The evolution cost is an important criterion on its own right, left for future studies.

Figure 6(d) presents the spectrum usage and transponder cost of the solutions obtained by ranging the optimization coefficients w for the flexible network and traffic of year 2018, that is, these solutions are calculated for the same input but different values of the coefficient w. The solutions found [represented by points in Fig. 6(d)] form the so-called Pareto front, that is, the solutions have the property that none of them has both optimization parameters better than any other solution. So if one of them is superior to another with respect to the spectrum used, it will be inferior to that with respect to the transponders' cost, and vice versa. Note that since we are using a heuristic, it is not guaranteed that for each value of w we get a solution that is at the Pareto front (we actually had to increase the number of SimAn iterations to 10,000 to obtain the solutions plotted in this graph).

Our algorithms are parametric in w, which can be viewed to represent the relation in the price of the spectrum and transponders. To reduce the used spectrum ($w \to 1$) a larger transponder cost is encountered, indicating that some transponders use transmission tuples with high modulation format (more bits/symbol) but low reach and low rate. On the other hand, minimizing the transponders' cost ($w \to 0$) selects tuples with the maximum total rate that might not use the highest possible modulation format. In Fig. 6(d) we see an interesting trade-off between the spectrum used and the transponder cost. Depending on the actual market prices of these two [25], a specific solution from the Pareto front would achieve the minimum overall cost and would be picked as the optimum for that particular instance.

VI. Conclusions

Flexible optical networks are receiving much attention as spectrally efficient solutions that can provide subwavelength and superwavelength granularity. We extend our previous work on planning flexible networks and propose algorithms that consider the physical layer in more detail, and select the transmission configuration, the breaking of demands into multiple connections, and the placement of regenerators. The algorithms take as input the feasible transmission options of the transponders, defined to account for the physical layer limitations. We formulate network planning as a multiobjective optimization problem with respect to the maximum spectrum and the cost of transponders used and present ILP and heuristic algorithms to solve it. The problem definition is very general and so are the proposed algorithms, which can be used in flexible and even in standard WDM optical networks. Our results show that the heuristic algorithms have near-optimal performance, close to that obtained with ILP formulations, at least for small-sized networks where we obtain the optimal solutions. Using realistic transmission specifications for optical OFDM networks, we compare the performance of a flexible OFDM network to that of a MLR WDM network and verify the gains that can be obtained through flexible optical networking. Using an optimization function that accounts for both the maximum spectrum used and the cost of the transponders, we observe interesting trade-offs between these optimization parameters in flexible networks.

Acknowledgments

This work was partially supported by the ICT IDEALIST project (grant agreement number 317999). The authors would like to thank I. Tomkos, A. Klekamp, and F. Buchali for help in defining the IA-RSA problem. Parts of this paper were presented in [26].

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