Nonlinear Impairment-Aware Static Resource Allocation in Elastic Optical Networks

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***Abstract*—This paper studies the routing, modulation format, and spectrum allocation problem in elastic fiber-optical networks for static traffic. Elastic networks, based on Nyquist wavelength-division multiplexing or optical orthogonal frequency-division multiplexing, can efficiently utilize the optical fiber's bandwidth in an elastic manner by partitioning the bandwidth into hundreds or even thousands of subcarriers. Beside the amplified spontaneous emission noise, the nonlinear impairments of each connection is explicitly considered by utilizing an analytical model to calculate the nonlinear interference from other connections propagating in the same fibers. The objective of our work is to minimize the bandwidth, i.e., the number of used subcarriers across the network, while satisfying the demands on throughput and quality for all connections. A novel integer linear program formulation and low-complexity heuristics are proposed. Simulation results are presented to demonstrate the effectiveness of the proposed approaches. Compared with transmission reach-based benchmark methods, our methods can achieve up to 31% bandwidth reduction.**

***Index Terms*—Elastic optical networks, NWDM, OOFDM, physical impairments, routing and spectrum assignment.**

I. Introduction

NEXT generation backbone networks should have the capability to deal with the ever increasing and heterogeneous traffic from various applications, such as e-science and inter data center communications, which makes elastic optical networks an ideal candidate, since they can flexibly and efficiently utilize the fiber bandwidth. Nyquist wavelength division multiplexing (NWDM) and optical orthogonal frequency division multiplexing (OOFDM) are technologies to enable elastic optical networks. The optical spectrum of each fiber (e.g., the C-band) is divided into subcarriers. The bandwidth of subcarrier is much smaller (e.g., 6.25 or 12.5 GHz) than the bandwidth of the wavelengths in a fixed grid wavelength division multiplexing (WDM)-based optical network (e.g., 50 GHz). A variety of modulation schemes (e.g., quadrature phase-shift keying (QPSK) and 16-point quadrature amplitude modulation (16-QAM)) can be adopted by different subcarriers and result in different bit rates. Therefore, only the required number of subcarriers need to be allocated to a service in order to satisfy its throughput requirement [1].

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There are three main challenges in the routing, modulation format, and spectrum allocation (RMSA) problem in elastic optical networks: (a) the spectrum continuity constraint, (b) the spectrum contiguity constraint, and (c) accounting for physical layer impairments. The spectrum continuity constraint ensures that, when there are no spectrum converters in the network, the same set of subcarriers are assigned on all the links of a lightpath. The spectrum contiguity constraint ensures that the subcarriers allocated to a connection are contiguous. Finally, physical layer impairments such as noise and crosstalk cause the quality of the optical signals to degrade as they traverse the network.

The connection requests for the RMSA problem can be static (offline) or dynamic (online). For static traffic, the connection requests in the form of a traffic matrix are given and fixed, rendering the RMSA problem into a planning problem. Once the planning state is completed, RMSA with dynamic traffic is considered during network operation, and connection requests arrive to and depart from the network following a stochastic process. In this paper, we focus exclusively on the static traffic problem.

A. Related Work

Most existing related work on impairment-aware RMSA in elastic optical networks are based on transmission-reach limits [2]–[7]. In these studies, each modulation format has a corresponding transmission reach limit, which depends only on the linear impairments. The quality of a path assigned a particular modulation format is assumed to be good as long as the length of the path is no longer than the corresponding transmission reach. In addition, in order to avoid any non-linear interference, a guard-band consisting of a number of subcarriers is inserted between two different connections that are assigned adjacent subcarrier bands. Nonlinear impairments were taken into account in Beyranvand et al. [8] to derive worst-case transmission reach limits, assuming a full network load. In particular, the concept of distance-adaptive spectrum resource allocation was first proposed in Jinno et al. [2]. This concept was applied to the RMSA problem for dynamic traffic in [3-5], and for static traffic in Christodoulopoulos et al. [6], using a novel integer linear programming (ILP) formulation and related heuristics. Finally, Christodoulopoulos *et al.* [7] considered the RMSA problem along with transponder allocation. However, the transmission-reach model fails to consider the actual nonlinear impairments (NLI), such as the interference among connections, which are dependent on the routing and resource allocation of connections over the same path. Hence, the reach and guard-band may overestimate or underestimate the connection impairments.

More sophisticated methods that account for NLI were studied for dynamic and static routing and wavelength assignment (RWA)[1] problems in fixed-grid WDM networks (e.g.,[9]–[14]). For the RMSA problem in elastic optical networks, effective methods were proposed for dynamic traffic in [8], for sequentially loaded traffic in [15], and for dynamic traffic allocation in elastic optical networks with multi-core fibers in [16]. The problem of static RMSA in elastic optical networks under a realistic NLI model was studied for the first time in our conference paper [17]. In this paper, we include mathematically complete and self-contained descriptions of the ILP formulations and algorithms that were used in [17]. Furthermore, the results in [17] are extended by improving the proposed heuristics adding two more connection sorting policies in both group ILP (GILP) and connection list (CL), adding K-shortest paths and using simulated annealing in CL; and one more network topology is used in simulations.

B. Contributions

To the best of our knowledge, the static RMSA problem has not been addressed in elastic optical networks when taking into consideration both linear impairments and NLI. We provide an RMSA method based on a novel ILP formulation, as well as several low-complexity heuristics. Through extensive simulations, we show that our algorithms exhibit better performance compared to the algorithms considering transmission reach limits and guard-bands in [6].

This paper is organized as follows. In Section II, we present the physical layer impairment model and the problem statement. The ILP formulation, proposed heuristics and benchmark algorithms are presented in Section III. Section IV presents and discusses the numerical results. We conclude the paper in Section V.

II. Physical Layer Impairment Model and Problem Statement

A. Physical Layer Impairment Model

Both amplified spontaneous emission noise (ASE) and NLI are considered by adopting the physical layer model proposed in [18]. Suppose connection i is allocated route r_i, then its signal-to-noise-ratio (SNR) is

$$\mathrm{SNR}_i = \frac{G}{G_{\mathrm{ASE}} + G_{\mathrm{NLI}}}, \tag{1}$$

where $G_{\mathrm{ASE}} = \sum_{l \in r_i} N_l G^0_{\mathrm{ASE}}$ and $G^0_{\mathrm{ASE}} = (e^{\alpha L} - 1) n_{sp} \mathsf{h}\nu$. Similarly, $G_{\mathrm{NLI}} = \sum_{l \in r_i} N_l G^l_{\mathrm{NLI}}$, and

$$G^l_{\mathrm{NLI}} = \mu\left(\ln(\rho B_i^2) + \sum_j \ln\frac{\Delta f_{ij} + B_j/2}{\Delta f_{ij} - B_j/2}\right). \tag{2}$$

The related parameters are defined in Table I. Eq. (2) is only valid for bandwidths of 28 GHz or more. The interested reader is referred to [18] for further details.

[1]The terminology of RWA is used in the WDM networks literature, where wavelengths are allocated to light-paths. In mixed line rate optical networks, modulation format allocation is part of RWA, since each line rate has a specific modulation format.

TABLE I
Parameters for SNR Calculation

Symbol	Meaning
G	signal power spectral density
G_{ASE}	PSD of ASE
G^0_{ASE}	PSD of ASE of a single span
G_{NLI}	PSD of NLI
G^l_{NLI}	PSD of NLI of a single span on link l
N_l	the number of spans (with one amplifier per span) on link l
L	the length of each span
α	the power attenuation
n_{sp}	the spontaneous emission factor
h	Planck's constant
ν	the optical carrier frequency
j	another connection using link l
B_i	the bandwidths for connections i
B_j	the bandwidths for connections j
Δf_{ij}	the center frequency spacing between connections i and j
γ	the fiber nonlinearity coefficient
β_2	the fiber dispersion
ρ	$(\pi^2 \lvert\beta_2\rvert)/\alpha$
μ	$(3\gamma^2 G^3)/(2\pi\alpha\lvert\beta_2\rvert)$

B. Problem Statement

The network consists of a set of nodes, which are connected by links. Each link consists of two fibers with opposite directions, on which a certain maximum bandwidth is available. This bandwidth is allocated by means of subcarrier modulation, realized as either OOFDM or NWDM. The spectrum is therefore allocated in multiples of the subcarrier bandwidth C_s. A set of connection requests between pairs of nodes should be simultaneously satisfied. For each connection in the network, a route, a modulation format, and a contiguous subcarrier band is allocated in order to satisfy its bit rate and SNR requirements. The goal is to minimize the maximum allocated subcarrier index on any link in the network, which corresponds to the maximum bandwidth. The set of static connection requests is represented by an all-to-all symmetric matrix. Each connection is bidirectional and the same resources are allocated in both directions.

III. Proposed Algorithms and Benchmark

To solve the RMSA problem, we first present an ILP formulation in Section III-A, that can deal with small problem instances. This approach is consistent with previous works, where small networks with 4–10 nodes were handled optimally using ILP, whereas various suboptimal heuristics were applied to larger networks with 14–28 nodes [6], [19], [20]. We then present two heuristics in Section III-B for larger instances. Finally, the benchmark ILP and heuristics are summarized in Section III-C.

A. ILP Formulation

The RMSA problem with the objective to minimize the maximum allocated subcarrier index on all links can be formulated as an ILP problem. The input parameters and variables used in the ILP are listed in Tables II and III, respectively. Thus, we can have the optimization problem as follows (as an extension of [6] by replacing the reach-based constraints with the GN model based-SNR constraints):

TABLE II
ILP INPUT PARAMETERS

Symbol	Meaning
$z_{ln} \in \mathbb{B} = \{0, 1\}$	$z_{ln} = 1$ if node n is an ending node of link l
$v_{in} \in \mathbb{B}$	$v_{in} = 1$ if n is source or destination of connection i
$\Lambda_i \in \mathbb{R}_{\geq 0}$	bit rate requirement of connection i
$T_{im} \in \mathbb{N}$	number of subcarriers of connection i when it is assigned modulation format m
$\text{SNR}_m \in \mathbb{R}_{\geq 0}$	SNR threshold of modulation format m
$J^{\text{crosstalk}}_{imh} = \mu \ln \frac{h+T_{im}}{h-T_{im}} \in \mathbb{R}_{\geq 0}$	the partial NLI introduced by connection i to another connection when i is assigned modulation format m and the center frequency spacing between them is $hC_s/2$, $h \in \mathbb{N}$ denotes the number of subcarrier half bandwidths
$H^{\text{NLI}}_{im} = \mu \ln\left(\rho (C_s T_{im})^2\right) \in \mathbb{R}_{\geq 0}$	the partial NLI of connection i when it is assigned modulation format m
$N_l \in \mathbb{N}$	number of spans on link l
$G \in \mathbb{R}_{\geq 0}$	signal power spectrum density
$G^0_{\text{ASE}} \in \mathbb{R}_{\geq 0}$	ASE noise power spectrum density per span
$\theta \in \mathbb{N}$	a large number

TABLE III
ILP VARIABLES

Symbol	Meaning
$B_i \in \mathbb{N}$	the number of subcarriers allocated to connection i
$f_i \in \mathbb{N}$	the lowest subcarrier index (first subcarrier index) allocated to connection i
$F \in \mathbb{N}$	the maximum allocated subcarrier index on any link
$p^{\text{link}}_{il} \in \mathbb{B}$	$p^{\text{link}}_{il} = 1$ if link l is on the route assigned to connection i
$p^{\text{node}}_{in} \in \mathbb{B}$	$p^{\text{node}}_{in} = 1$ if node n is on the route assigned to connection i
$\mathcal{M}^{\text{mod}}_{im} \in \mathbb{B}$	$\mathcal{M}^{\text{mod}}_{im} = 1$ if connection i is assigned modulation format m
$y^{\text{share}}_{ij} \in \mathbb{B}$	$y^{\text{share}}_{ij} = 1$ if connection i and connection j share at least one common link
$u^{\text{share}}_{ij} \in \mathbb{B}$	$u^{\text{share}}_{ij} = 1$ if $y^{\text{share}}_{ij} = 1$ and $f_i + B_i \leq f_j$
$\Delta^{(h)}_{ijm} \in \mathbb{B}$	$\Delta^{(h)}_{ijm} = 1$ if the center frequency spacing between connection i and connection j is $hC_s/2$ ($h \in \mathbb{N}$ denotes the number of subcarrier half bandwidths) and $\mathcal{M}^{\text{mod}}_{jm} = 1$
$w^{\text{crosstalk}}_{ijl} \in \mathbb{R}_{\geq 0}$	upper bound of the NLI to connection i from connection j on link l
$t^{\text{NLI}}_{il} \in \mathbb{R}_{\geq 0}$	upper bound of G^l_{NLI} of connection i on link l

$$\text{minimize} \quad F \tag{3a}$$

s.t.

$$\sum_m \mathcal{M}^{\text{mod}}_{im} = 1 \quad \forall i \tag{3b}$$

$$B_i = \sum_m T_{im} \mathcal{M}^{\text{mod}}_{im} \quad \forall i \tag{3c}$$

$$F \geq f_i + B_i - 1 \quad \forall i \tag{3d}$$

$$\sum_l p^{\text{link}}_{il} z_{ln} = 2p^{\text{node}}_{in} - v_{in} \quad \forall i, n \tag{3e}$$

$$p^{\text{link}}_{il} + p^{\text{link}}_{jl} \leq 1 + y^{\text{share}}_{ij} \quad \forall i, j \neq i, l \tag{3f}$$

$$f_i + B_i - f_j \leq \theta(1 - u^{\text{share}}_{ij}) \quad \forall i, j \neq i \tag{3g}$$

$$f_j + B_j - f_i \leq \theta(1 - y^{\text{share}}_{ij} + u^{\text{share}}_{ij}) \quad \forall i, j \neq i \tag{3h}$$

$$G \sum_m \mathcal{M}^{\text{mod}}_{im} / \text{SNR}_m \geq G^0_{\text{ASE}} \sum_l p^{\text{link}}_{il} N_l + \sum_l N_l t^{\text{NLI}}_{il} \quad \forall i \tag{3i}$$

$$t^{\text{NLI}}_{il} \geq \theta(p^{\text{link}}_{il} - 1) + \sum_m \mathcal{M}^{\text{mod}}_{im} H^{\text{NLI}}_{im} + \sum_{j \neq i} w^{\text{crosstalk}}_{ijl} \; \forall i, l \tag{3j}$$

$$w^{\text{crosstalk}}_{ijl} \geq \theta(p^{\text{link}}_{jl} - 1) + \sum_{m,h} \Delta^{(h)}_{ijm} J^{\text{crosstalk}}_{jmh} \quad \forall i, j \neq i, l \tag{3k}$$

$$\sum_h \Delta^{(h)}_{ijm} = \mathcal{M}^{\text{mod}}_{jm} \quad \forall i, j \neq i, m \tag{3l}$$

$$\sum_{m,h} h\Delta^{(h)}_{ijm} \leq \theta(1 - u^{\text{share}}_{ij}) + 2(f_j - 1) + B_j - 2(f_i - 1) - B_i \quad \forall i, j \neq i \tag{3m}$$

$$\sum_{m,h} h\Delta^{(h)}_{ijm} \leq \theta(1 - y^{\text{share}}_{ij} + u^{\text{share}}_{ij}) + 2(f_i - 1) + B_i - 2(f_j - 1) - B_j \quad \forall i, j \neq i. \tag{3n}$$

The constraints are to be interpreted as follows: (3b) ensures that each connection is assigned only one modulation format; (3c) ensures that the number of subcarriers allocated to each connection depends on the modulation format assigned to this connection; (3d) ensures that the last allocated subcarrier index of each connection i (i.e., $f_i + B_i - 1$) does not exceed F; (3e) ensures that one no-loop route is allocated to each connection[2] (3f) ensures that $y^{\text{share}}_{ij} = 1$ when connections i and j share at least one common link; (3g) and (3h) ensure that when there is at least one common link shared by two connections i and j, the spectrum allocated to them should not have any overlapping;[3] (3i) ensures the satisfaction of the SNR requirement for connection i considering the PSDs of ASE noise and NLI; (3j) determines the NLI PSD of connection i on link l; [4] (3k) determines the NLI PSD from connection j to connection i on link l;[5] (3l)–(3n) bound the value of $\Delta^{(h)}_{ijm}$: (3l) ensures that $\sum_h \Delta^{(h)}_{ijm} = 1$ when connection j is assigned modulation format m, i.e., $\mathcal{M}^{\text{mod}}_{jm} = 1$; and (3m) and (3n) ensure that $\sum_{m,h} h\Delta^{(h)}_{ijm}$ is no larger than[6] the central frequency spacing between connections i and j, accounting for the cases where connection i is placed in a lower or a higher frequency band than connection j.

The number of variables and constraints in the ILP formulation depends on the number of connection requests I, the number of links L, the number of nodes N in the network, the

[2] If node n is on the route of connection i (but not source or destination node of connection i), then two of the links ending with n should be on the route, i.e., if $p^{\text{node}}_{in} = 1$ and $v_{in} = 0$, then $\sum_l p^{\text{link}}_{il} z_{ln} = 2$; if node n is the source or destination node of connection i, then only one of the links ending with n should be on the route, i.e., if $p^{\text{node}}_{in} = 1$ and $v_{in} = 1$, then $\sum_l p^{\text{link}}_{il} z_{ln} = 1$.

[3] Constraints of the form $a \leq \theta b + c$ are always true when $b > 0$, by choice of a sufficiently large value of θ.

[4] If link l is not on the route of connection i, i.e., $p^{\text{link}}_{il} = 0$, then (3j) is inactive. If $p^{\text{link}}_{il} = 1$, then $t^{\text{NLI}}_{il} \geq \sum_m \mathcal{M}^{\text{mod}}_{im} H^{\text{NLI}}_{im} + \sum_{j \neq i} w^{\text{crosstalk}}_{ijl}$, where the right side is the value of NLI of connection i on link l.

[5] If link l is not on the route of connection j, i.e., $p^{\text{link}}_{jl} = 0$, then (3k) is inactive. On the other hand, if $p^{\text{link}}_{il} = 1$, then $w^{\text{crosstalk}}_{ijl} \geq \sum_{m,h} \Delta^{(h)}_{ijm} J^{\text{crosstalk}}_{jmh}$, where the right side is the value of NLI to connection i from connection j.

[6] According to (2), the nonlinear effect from connection j to connection i ($w^{\text{crosstalk}}_{ijl}$ in the ILP formulation) increases as the central frequency spacing $\sum_{m,h} h\Delta^{(h)}_{ijm}$ decreases. Therefore, the ILP will set $\sum_{m,h} h\Delta^{(h)}_{ijm}$ to be equal to the actual central frequency spacing when necessary.

number of subcarriers on each link S, and the number of total modulation format M. In particular, $2I+1$ integer variables, $2I^2+I^2MS+IL+IN+IM$ boolean variables, and I^2L+IL real variables. $I+IN+I^2M$ boolean equality constraints for (3b), (3e) and (3l); I^2L boolean inequality constraints for (3f); I integer equality constraints for (3c); $I+4I^2$ integer inequality constraints for (3d), (3g), (3h), (3m) and (3n); and $I+IL+I^2L$ real inequality constraints for (3i), (3j) and (3k).

B. Proposed Heuristics

Although the routing, modulation format, and spectrum assignment of all connections can be optimally solved by the ILP, it is very time consuming due to the involved integer constraints, and it can only provide optimal results for small networks with a few connection requests within a reasonable time. Therefore, two heuristics, GILP and CL, are proposed for dealing with larger networks. In GILP, the requests are split into smaller groups and the requests within a group are optimally allocated using ILP, with the groups being sequentially processed. In CL, requests are allocated one by one. When allocating one connection (or group of connections), the crosstalk from previously allocated connections will be considered. The algorithms also take the interference from $E \geq 1$ future connection requests (in GILP, these are the connections in next groups) into consideration by including an adaptive SNR margin. The interference from a future connection depends on its routing, modulation format, and central frequency, which are not known at this moment. To account for this, we make a conservative estimate: for the routing, we precompute K shortest paths [21] for each connection i, and let $q'_{il}=1$ if any of the K paths for connection i uses link l. In terms of the modulation format, according to (2), the crosstalk to connection i from connection j depends on

$$\ln\frac{\Delta f_{ij}+B_j/2}{\Delta f_{ij}-B_j/2}=\ln\left(1+\frac{B_j}{\Delta f_{ij}-B_j/2}\right). \quad (4)$$

Therefore, the crosstalk achieves its maximum value when connection j is assigned the lowest modulation format (i.e., largest bandwidth), and when $\Delta f_{ij}-B_j/2$ takes its minimum possible value (note that it is not dependent on the bandwidth of connection i). We will assume these crosstalk values for the future E connections.

Connection Ordering Policies: In both heuristics, the connections are first sorted by one of the three policies:[7]

i) decreasing order of their bit rate requirements Λ_i;
ii) decreasing order of number of links on their shortest paths;
iii) decreasing order of Λ_i times shortest path length.

The impact of these orderings will be evaluated in the numerical results. We now present the two heuristics in detail.

1) Group ILP (GILP): After ordering according to one of the three policies, GILP divides the connections into groups of size $\eta \geq 1$ (except the last group, whose size may be less than η). Each group is denoted as Θ_a for $1 \leq a \leq \lceil I/\eta \rceil$, where I is the total number of connection requests. Then, a modification of ILP in (3) is called for each group.

[7] We also tried the sorting policy that the connections are sorted in decreasing order of their shortest path length, but its performance is dominated by other policies in all simulated cases in this paper.

TABLE IV
GILP Additional Variables

Symbol	Meaning
$f'_{iel} \in \mathbb{N}$	the lowest subcarrier index (first subcarrier index) allocated to connection e on link l with respect to connection i
$y'_{iel} \in \mathbb{B}$	$y'_{iel}=1$ if both connection i and connection e use link l
$u'_{iel} \in \mathbb{B}$	$u'_{iel}=1$ if $y'_{iel}=1$ and $f_i+B_i \leq f'_{iel}$
$\Delta'^{(h)}_{iel} \in \mathbb{B}$	$\Delta'^{(h)}_{iel}=1$ if on link l, $\Delta f_{ie}-B_e/2=C_s h/2$, where Δf_{ie} is calculated based on f'_{iel}, $h \in \mathbb{N}$ denotes the number of subcarrier half bandwidths

For a particular group a, denote the set of already allocated connections (i.e., the connections that belong to previous groups) as $\Gamma=\cup_{a'=1}^{a-1}\Theta_{a'}$, and the set of E future connections as Ψ. Besides the variables in Table III, additional variables are needed as shown in Table IV. This notation now allows us to formulate the following optimization problem for group a.

$$\text{minimize}$$
$$\begin{cases}\theta F+\sum\limits_{i\in\Theta_a,e\in\Psi,l,h} h\Delta'^{(h)}_{iel}, \text{ if } a=\lceil I/\eta\rceil\\ \theta F+\sum\limits_{i\in\Theta_a}(f_i+B_i+\sum\limits_m m\mathcal{M}^{\text{mod}}_{im})+\sum\limits_{i\in\Theta_a,e\in\Psi,l,h} h\Delta'^{(h)}_{iel} \\ \qquad \text{otherwise}\end{cases} \quad (5a)$$

$$\text{s.t.}$$

$$\sum_m \mathcal{M}^{\text{mod}}_{im}=1 \quad \forall i\in\Theta_a \quad (5b)$$

$$B_i=\sum_m T_{im}\mathcal{M}^{\text{mod}}_{im} \quad \forall i\in\Theta_a \quad (5c)$$

$$F\geq f_i+B_i-1 \quad \forall i\in\Theta_a \quad (5d)$$

$$\sum_l p^{\text{link}}_{il}z_{ln}=2p^{\text{node}}_{in}-v_{in} \quad \forall i\in\Theta_a, n \quad (5e)$$

$$p^{\text{link}}_{il}+p^{\text{link}}_{jl}\leq 1+y^{\text{share}}_{ij}\ \forall i\in\Gamma\cup\Theta_a, j\in\Gamma\cup\Theta_a\setminus i, l \quad (5f)$$

$$f_i+B_i-f_j\leq\theta(1-u^{\text{share}}_{ij})\ \forall i\in\Theta_a, j\in\Gamma\cup\Theta_a\setminus i \quad (5g)$$

$$f_j+B_j-f_i\leq\theta(1-y^{\text{share}}_{ij}+u^{\text{share}}_{ij})\ \forall i\in\Theta_a, j\in\Gamma\cup\Theta_a\setminus i \quad (5h)$$

$$G\sum_m \mathcal{M}^{\text{mod}}_{im}/\text{SNR}_m\geq G^0_{\text{ASE}}\sum_l(p^{\text{link}}_{il}N_l)+\sum_l N_l t^{\text{NLI}}_{il}, \forall i\in\Theta_a \quad (5i)$$

$$t^{\text{NLI}}_{il}\geq\theta(p^{\text{link}}_{il}-1)+\sum_m\mathcal{M}^{\text{mod}}_{im}H^{\text{NLI}}_{im}+\sum_{j\in\Gamma\cup\Psi\cup\Theta_a\setminus i} w^{\text{crosstalk}}_{ijl}, \quad \forall i\in\Theta_a, l \quad (5j)$$

$$w^{\text{crosstalk}}_{ijl}\geq\theta(p^{\text{link}}_{jl}-1)+\sum_{m,h}\Delta^{(h)}_{ijm}J^{\text{crosstalk}}_{jmh} \quad \forall i\in\Theta_a\cup\Gamma, j\in\Gamma\cup\Theta_a\setminus i, l \quad (5k)$$

$$\sum_h\Delta^{(h)}_{ijm}=\mathcal{M}^{\text{mod}}_{jm}\ \forall i\in\Theta_a\cup\Gamma, j\in\Gamma\cup\Theta_a\setminus i, m \quad (5l)$$

$$\sum_{m,h}h\Delta^{(h)}_{ijm}\leq\theta(1-u^{\text{share}}_{ij})+2(f_j-1)+B_j$$

$$-2(f_i-1)-B_i \quad \forall i\in\Theta_a\cup\Gamma, j\in\Gamma\cup\Theta_a\setminus i \tag{5m}$$

$$\sum_{m,h} h\Delta_{ijm}^{(h)} \le \theta(1-y_{ij}^{\text{share}}+u_{ij}^{\text{share}})+2(f_i-1)+B_i$$

$$-2(f_j-1)-B_j \quad \forall i\in\Theta_a\cup\Gamma, j\in\Gamma\cup\Theta_a\setminus i \tag{5n}$$

$$p_{il}^{\text{link}}+q'_{el}\le 1+y'_{iel} \quad \forall i\in\Theta_a\cup\Gamma, e\in\Psi, l \tag{5o}$$

$$f_i+B_i-f'_{iel}\le\theta(1-u'_{iel}) \quad \forall i\in\Theta_a\cup\Gamma, e\in\Psi, l \tag{5p}$$

$$f'_{iel}+T_{eM}-f_i\le\theta(1-y'_{iel}+u'_{iel}), \forall i\in\Theta_a\cup\Gamma, e\in\Psi, l \tag{5q}$$

$$\varphi_i\ge\sum_l N_l\sum_{j\in\Theta_a} w_{ijl}^{\text{crosstalk}} \quad \forall i\in\Gamma \tag{5r}$$

$$w_{iel}^{\text{crosstalk}}=q'_{el}\sum_h\Delta_{iel}^{\prime(h)}X_{eh} \quad \forall i\in\Theta_a, e\in\Psi, l \tag{5s}$$

$$\sum_h h\Delta_{iel}^{\prime(h)}\le\theta(1-u'_{iel})+2(f'_{iel}-1)-2(f_i-1)-B_i$$

$$\forall i\in\Theta_a, e\in\Psi, l \tag{5t}$$

$$\sum_h h\Delta_{iel}^{\prime(h)}\le\theta(1-y'_{iel}+u'_{iel})+2(f_i-1)+B_i$$

$$-2(f'_{iel}-1)-2T_{eM} \quad \forall i\in\Theta_a, e\in\Psi, l. \tag{5u}$$

Constraints (5b)–(5n) are the equivalents of (3b)–(3n), except that the values of $p_{il}^{\text{link}}, p_{in}^{\text{node}}, \mathcal{M}_{im}^{\text{mod}}, f_i$, and B_i of each connection $i\in\Gamma$ are known inputs, instead of variables. Constraints (5o)–(5u) are included to protect against interference from future connection requests, in which we introduce the following notation: in (5r), $\varphi_i\in\mathbb{R}_{\ge 0}$ denotes the remaining SNR of connection $i\in\Gamma$, which is calculated as $\varphi_i=G/\text{SNR}_{\text{req}}-G_{\text{ASE}}-G'_{\text{NLI}}$, where SNR_{req} is the required SNR, according to the modulation scheme assigned to connection i, to achieve a certain threshold BER value, G_{ASE} is the PSD of ASE for connection i (depending on its route), and G'_{NLI} is the PSD of the NLI according to the resource allocation to connections in Γ. Note that φ_i is an input to the ILP in (5); T_{em} is the number of subcarriers requirement for connection e when allocated modulation format m and $X_{eh}=\mu\ln(1+2T_{e1}/h)$. Hence T_{eM} is the smallest bandwidth requirement for connection e and X_{eh} is the largest crosstalk to connection i from connection e.

The number of variables and constraints in the GILP formulation depends on the number of connection requests in each group η, the number of future connection requests E, the number of links L, the number of nodes N in the network, the number of subcarriers on each link S, and the number of total modulation format M. In particular, $2\eta+1+\eta EL$ integer variables, $2\eta^2+\eta^2MS+\eta L+\eta N+\eta M+2\eta EL+\eta ESL$ boolean variables, and $\eta^2L+\eta L$ real variables. $\eta+\eta N+2\eta IM$ boolean equality constraints for (5b), (5e) and (5l); $2\eta IL+IEL$ boolean inequality constraints for (5f) and (5o); η integer equality constraints for (5c); $\eta+2\eta IL+2\eta I+2IEL+2\eta EL$ integer inequality constraints for (5d), (5g), (5h), (5m), (5n), (5p), (5q), (5t) and (5u); ηEL real equality constraints for (5s); and $\eta+\eta L+2\eta IL+I$ real inequality constraints for (5i), (5j), (5k) and (5r).

After solving (5) for the group Θ_a, the values of φ_i, $i\in\Gamma$ are updated (by adding the NLI from connections $\in\Theta_a$ to G'_{NLI}) and φ_i, $i\in\Theta_a$ are computed (by calculating the value of $G/\text{SNR}_{\text{req}}-G_{\text{ASE}}-G'_{\text{NLI}}$, where G'_{NLI} includes the NLI PSD from connections in $\Theta_a\cup\Gamma$). In case (5) is not feasible, this means that the choice of E was too aggressive and must be increased. All requests are then re-processed with a larger value of E, thus accounting for more nonlinear crosstalk from future connections. As E increases, the SNR_{req} for previous allocated connections decreases, therefore, there may be feasible solutions for current group without exceeding the SNR_{req} (with increased E) of previous allocated groups.

All together, this leads to the GILP method, summarized in Algorithm 1.

Algorithm 1 GILP algorithm

Step 1: Sort the connections according to policies (i), (ii) or (iii)
Step 2: Divide the sorted connections into groups Θ_a for $1\le a\le\lceil I/\eta\rceil$
Step 3: Set margin window $E=1$
Step 4:
for each group $a=1,2,\ldots,\lceil I/\eta\rceil$ **do**
  Solve the ILP in (5) for group Θ_a
  if a solution is found **then**
    Update φ_i, $i\in\Gamma$ and calculate φ_i, $i\in\Theta_a$
  else {ILP in (5) infeasible}
    $E=E+1$; **goto** Step 4
  end if
end for

2) Connection List (CL): In CL, we allocate the connections one by one. For each connection, we utilize the K minimum cost paths algorithm [21]. Connections are assumed to be ordered according to a certain policy.

Before formulating the CL algorithm, we introduce the following new notation: f_i denotes the first subcarrier index allocated to connection i; ω_i denotes the last subcarrier index allocated to connection i; $\sigma_{sl}\in\mathbb{B}$ denotes the state of subcarrier s on link l, with $\sigma_{sl}=1$ if the subcarrier s on link l is available; $p_{il}^{\text{link}}=1$ if link l is on the route r_i of connection i; and m_i denotes the modulation level allocated to connection i. For connection i, given a certain trial modulation format m' and a certain first subcarrier index f', we associate a cost c_l with each link l, defined as, equation (6) shown at the bottom of the page in which $c_l^{\text{past}}=N_l\mu\sum_{j=1}^{i-1}p_{jl}^{\text{link}}\ln[(\Delta f_{ij}+B_j/2)/(\Delta f_{ij}-B_j/2)]$ is the partial NLI from each previously allocated connection j whose route includes link l, and $c_l^{\text{fut}}=N_l\sum_{e=i+1}^{i+E}q'_{el}X'_{eh'}$ is the estimated NLI from E future connections. Here $X'_{eh'}=\mu\ln[1+T_{e1}/(h'-T_{eM}/2)]$ and h' is the smallest possible central frequency spacing between the connection i and e with the assumption that the modulation format allocated to connection i is m', the first subcarrier index allocated to connection i is f', and the modulation format for connection e is M (the highest one). Note that $c_l=\infty$ if any subcarrier $f'\le s\le f'+T_{im'}-1$ is not available.

The CL method now operates as follows: we initialize $E = 1$, $\omega_i = +\infty$ for every connection i, and $\sigma_{sl} = 1$ for all s, l. Then, for each connection i, ordered according to a given policy, every possible modulation format $1 \le m' \le M$, and every possible first subcarrier index f' will be tried. For each (m', f') candidate, K' minimum cost paths will be determined [21], utilizing the link costs in (6).

For each of the K' candidate paths for connection i (with modulation format candidate m' and first subcarrier index candidate f'), we check two conditions: (C-1) the SNR requirement of connection i should be satisfied, i.e., $\sum_{l \in \mathrm{path}} c_l \le G/\mathrm{SNR}_{m'}$, and (C-2) the SNR requirement of each previously allocated connection $j < i$ is not violated after allocating connection i with the candidate path, modulation formation m', and first subcarrier f'. Finally, the route, modulation format, and first subcarrier index for connection i will be selected as the one that achieves the smallest ω_i. If there is no feasible allocation for connection i, then we set $E = E + 1$, and we repeat the whole allocation procedure for all connections. The algorithm is summarized in Algorithm 2.

Algorithm 2 CL algorithm

Step 1: Sort the connections
Step 2: Set margin window $E = 1$
Step 3: Set $p_{il}^{\mathrm{link}} = 0; \forall(i, l); \omega_i = +\infty\ \forall i; \sigma_{sl} = 1\ \forall(s, l)$
for each connection i **do**
  for each modulation format m' and each first subcarrier index f' **do**
    if $T_{im'} + f' - 1 < \omega_i$ **then**
      for each link l **do**
        Assign cost c_l according to (6)
      end for
      Find the K' minimum cost paths for connection i
      Call function CHECK
    end if
  end for
  if r_i, f_i, and ω_i have been assigned to i **then**
    Update $p_{il}^{\mathrm{link}} = 1$ for links $l \in r_i$, set $\sigma_{sl} = 0$ for $s \in [f_i, \omega_i]$
  else {no path satisfied (C-1) and (C-2)}
    $E = E + 1$; **goto** Step 3
  end if
end for

We utilize simulated annealing to improve the CL heuristic performance (CL-SimAn). Simulated annealing is performed by the MATLAB built-in simulated annealing heuristic with default reannealing policy, temperature function, and acceptance function (i.e., the function used to determine whether a new point is accepted or not). For the required custom annealing function, a trial point for the problem is an ordering of connections. The custom annealing function for the problem will take the connection order with connection ordering policy (i) as input. The annealing function then modifies this ordering and returns a new ordering (i.e., a new point) by interchanging a uniformly selected connection with another uniformly selected connection. An objective function for the problem is another required input. The objective function returns the maximum allocated subcarrier index on any link for a given ordering. The proposed CL heuristic, without the connection sorting step (i.e., Step 1 in Algorithm 2 is removed) is used as the objective function. The SimAn algorithm stops if the number of iterations exceeds a maximum number of iterations, which is set to 10 000 in all SimAn simulations.

Algorithm 3 CHECK

for each path P of the K' minimum cost paths **do**
  if (C-1) and (C-2) are satisfied **then**
    Update $m_i \leftarrow m'$, $f_i \leftarrow f'$, $\omega_i \leftarrow T_{im'} + f' - 1$, and $r_i \leftarrow P$, **exit** (return back to CL algorithm)
  end if
end for

C. Benchmarks

To compare the performance of our proposed ILP, GILP, and CL methods, we utilize the ILP and heuristics proposed in [6] as benchmarks. The benchmark relies on a combination of transmission reach limits and guard-band, in order to deal with physical layer impairments. In particular, there is a transmission reach limit R_m for each modulation format m, so that a path longer than R_m cannot be assigned modulation format m. A guard-band of g subcarriers is used to avoid the interference between connections, instead of estimating the actual NLI. For each pair of nodes, $K = 3$ paths are precomputed based on a proposed modified shortest path algorithm[6]. The route for each connection is then selected from the corresponding K paths. These algorithms are summarized here, while the interested reader is referred to [6] for further details.

1) ILP: An ILP formulation for the RMSA problem based on transmission reach limit was presented in [6].

2) RML+SA ILP: The RMSA problem is divided into two subproblems: the routing and modulation level assignment (RML) problem, and the spectrum assignment (SA) problem. The subproblems are solved sequentially. In other words, the SA problem uses the output of RML problem. The ILP formulation in [6] is applied to each subproblem. For large network, since it takes a lot of time to obtain the optimal solution for SA problem, its ILP program is aborted after a fixed period of time, so the recorded results might not be optimal.

3) RMSA Heuristic: The RMSA heuristic allocates the connections one by one. The connections are sorted by (i) decreasing order of their bit rate requirements Λ_i; or (ii) decreasing

$$c_l = \begin{cases} +\infty, & \text{if } \exists s \in [f', f' + T_{im'} - 1] : \sigma_{sl} = 0 \\ N_l G_{\mathrm{ASE}}^0 + N_l \mu \ln(\rho T_{im'}^2) + c_l^{\mathrm{past}} + c_l^{\mathrm{fut}} & \text{otherwise,} \end{cases} \tag{6}$$

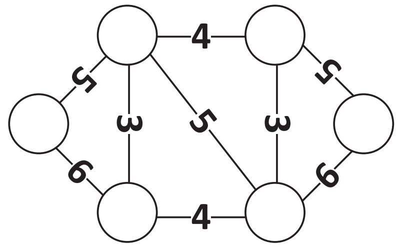


Fig. 1. Six-node network. The number on each link corresponds to the number of spans.

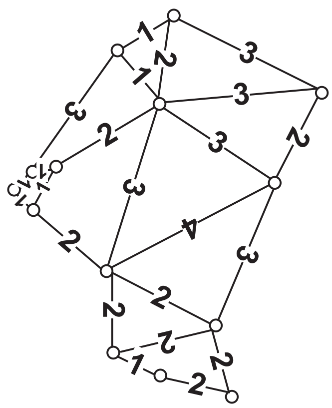


Fig. 2. Fourteen-node DT network. The number on each link corresponds to the number of spans.

order of the number of links on their shortest paths. For each of the K paths of every pair of nodes, the modulation format of the path is assigned as the highest-order modulation format whose reach limit R_m is longer than or equal to the length of the path. For each connection, the algorithm calculates the spectrum availability of all the candidate K paths based on the spectrum availability of links on the paths. The algorithm selects the path whose first available and sufficient subcarrier-band (i.e., the subcarrier-band is wide enough for the bandwidth requirement T_{im} of the current connection i) has the lowest first subcarrier index. In addition to the two connection sorting policies, a simulated annealing (SimAn) method was used to improve the performance of the RMSA heuristic by finding good ordering of the connections. There is a fixed transmission reach limit for each modulation format with a particular signal power in [6]. In order to deal with different values of power spectral density G in this work, we set the reach for modulation format m as $\lfloor G/(\mathrm{SNR}_m G^0_{\mathrm{ASE}}) \rfloor$ spans.

IV. Numerical Results

A. Simulation Settings

There are two network topologies for simulations: a small six-node network (see Fig. 1) and the larger 14-node Deutsche Telekom (DT) network (see Fig. 2). The number on each link corresponds to the number of spans. The parameters related to physical impairments are $\alpha = 0.22$ dB/km, $\gamma = 1.32$ $(\mathrm{W{\cdot}km})^{-1}$, $\beta_2 = -21.7$ ps^2/km, $n_{sp} = 1.8$, $\nu = 193$ THz, $L =$

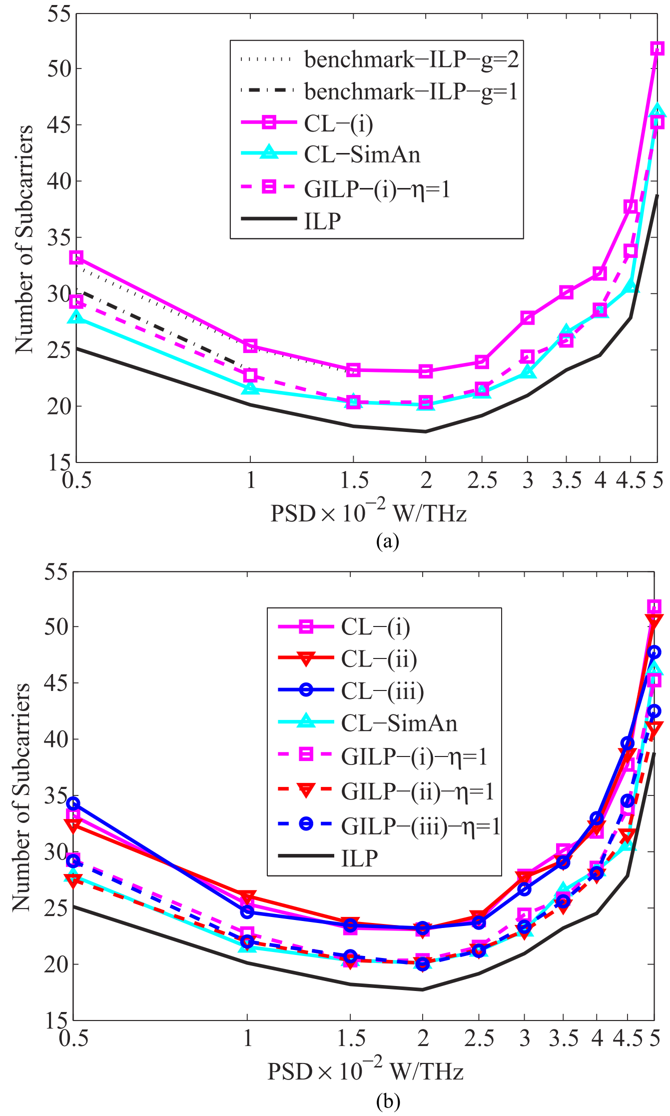


Fig. 3. Bandwidth (average of maximum allocated subcarrier indexes) versus PSD (see G in Table I) for the bit rate requirement of each connection is between 312.5 and 625 Gb/s in the six-node network. (a) Main algorithms compared with benchmarks. (b) Proposed algorithms, including the sorting policies.

100 km, and $C_s = 12.5$ GHz [22], [23]. The bit error rate (BER) requirement for all connections is set to 10^{-3}. There are $M = 4$ modulation formats: BPSK, QPSK, 8-QAM, and 16-QAM. We consider two kinds of bit rate requirements: the low bit rate requirement of each connection is uniformly distributed from 312.5 to 625 Gb/s; the high bit rate requirement of each connection is uniformly distributed from 1250 to 3750 Gb/s[8]. K is set to be 3 for the CL, GILP heuristics and benchmark algorithms, and $K' = 5$ for the CL heuristic. The guardband used for the benchmark methods is set to $g = 1$ and $g = 2$ subcarriers. For each simulation, the maximum allocated subcarrier index (on

[8]The lowest bit requirement ensures that even with the 16QAM modulation format, the number of allocated subcarriers is more than three, which is larger than the 28 GHz bandwidth limit with the physical layer model (see Section II-A).

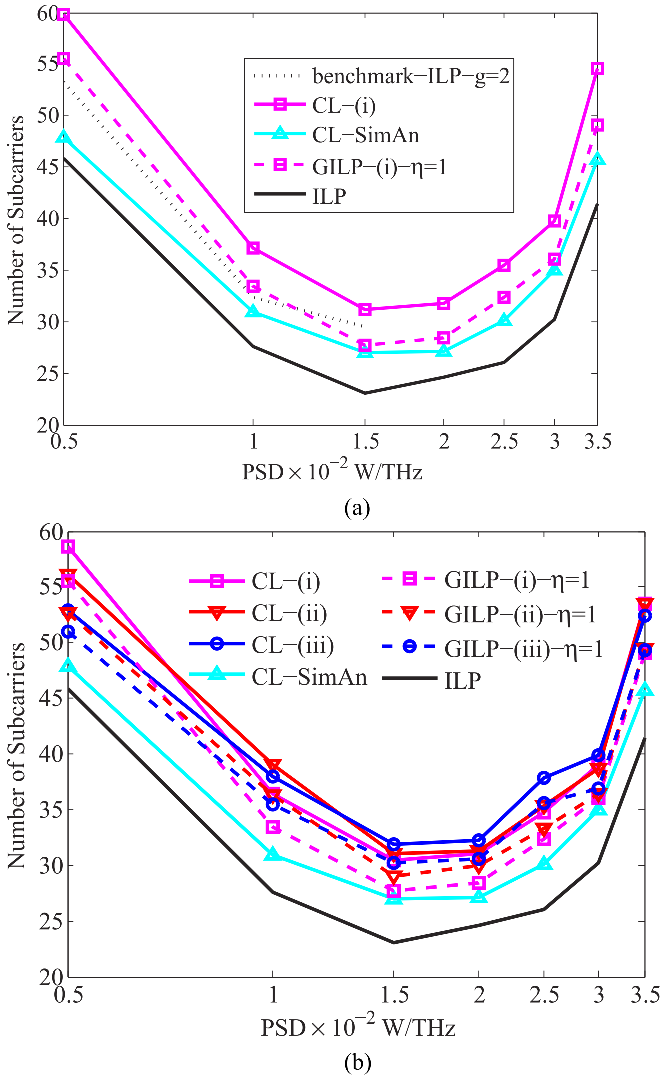


Fig. 4. Bandwidth (average of maximum allocated subcarrier indexes) versus PSD (see G in Table I) for the bit rate requirement of each connection is between 312.5 and 625 Gb/s in the six-node network with doubled link length. (a) Main algorithms compared with benchmarks. (b) Proposed algorithms, including the sorting policies.

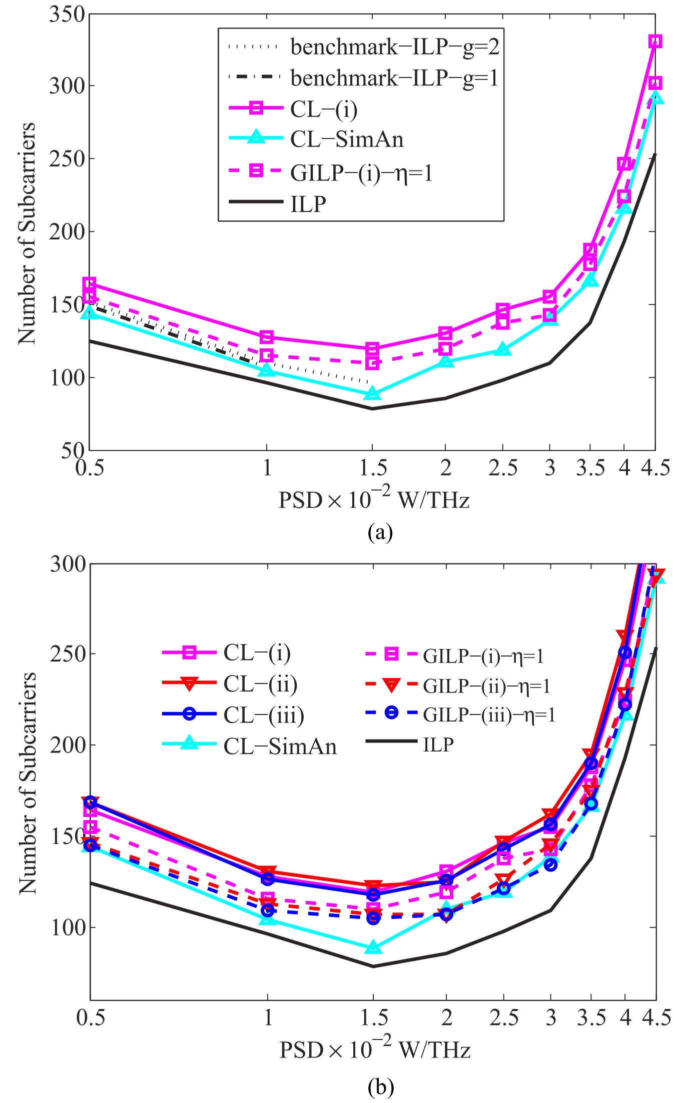


Fig. 5. Bandwidth (average of maximum allocated subcarrier indexes) versus PSD (see G in Table I) for the bit rate requirement of each connection is between 1250 and 3750 Gb/s in the six-node network. (a) Main algorithms compared with benchmarks. (b) Proposed algorithms, including the sorting policies.

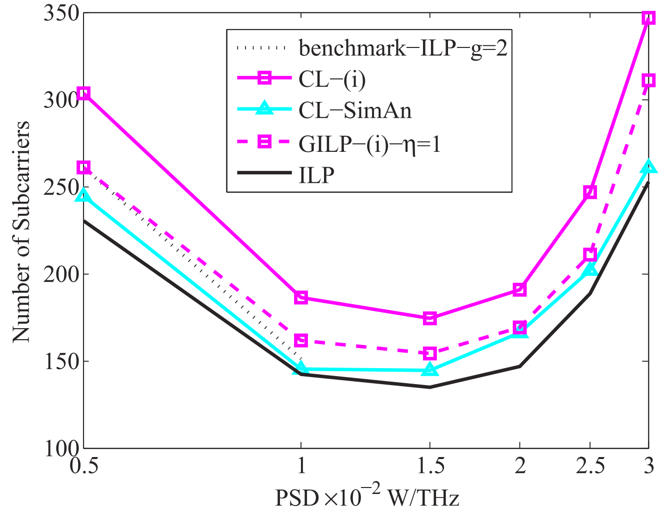
any link in the topologies) is recorded. Ten connection request matrices are generated, and the average results are shown in the following results figures.

B. Results for six-node Network

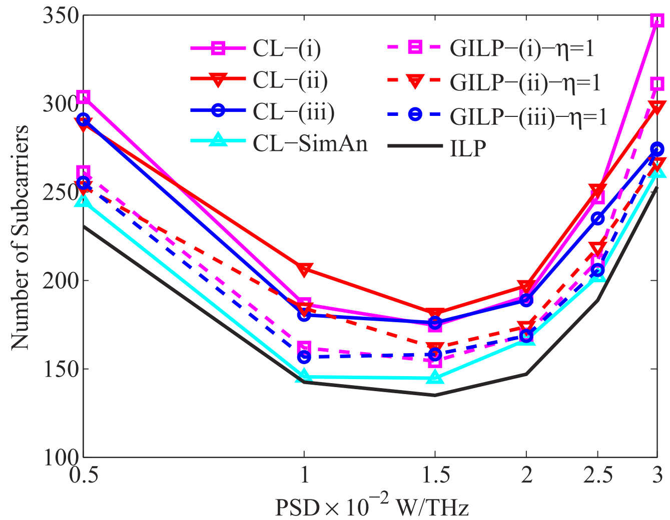
For the small six-node network, the results for the proposed ILP, proposed heuristics (CL and GILP) with three connection sorting policies (CL-(i), CL-(ii), CL-(iii), GILP-(i), GILP-(ii), and GILP-(iii), respectively), CL-SimAn, and the benchmark ILP are compared. We run the simulations on a desktop computer with four-core, i7-2600 CPU @3.40 GHz, and 8 GB RAM. The typical running time for ILP is 3 h. The GILP (with group size $\eta = 1$) for one E value is 10 min, but it may need to run multiple E values to get a feasible solution.

When the bit rate requirement of each connection is between 312.5 and 625 Gbps, the resulting average maximum bandwidths as a function of the PSD (see G in Table I) for the small network is shown in Fig. 3. As shown in Fig. 3(a), at higher PSD values, the guardband with one and two subcarriers in the benchmark ILP is insufficient to account for the NLI, rendering the optimization infeasible. SimAn and GILP-(i) with group size $\eta = 1$ have better performance than CL-(i). The optimal ILP saves 15% bandwidth over CL-SimAn when $G = 0.02$ W/THz. As shown in Fig. 3(b), since the shortest path distances and the bandwidth requirements for the connections are similar to each other, the sorting policies do not affect the results much. CL-SimAn has better results than all CL algorithms with different policies (i)–(iii). Also, the results of GILP with group size $\eta = 1$ are better than the CL algorithms.

After scaling the network topology by doubling each link length as in [7], we get the results in Fig. 4. In this case, the guardband with one subcarrier in the benchmark ILP fails to produce feasible solutions; compared with the network with the

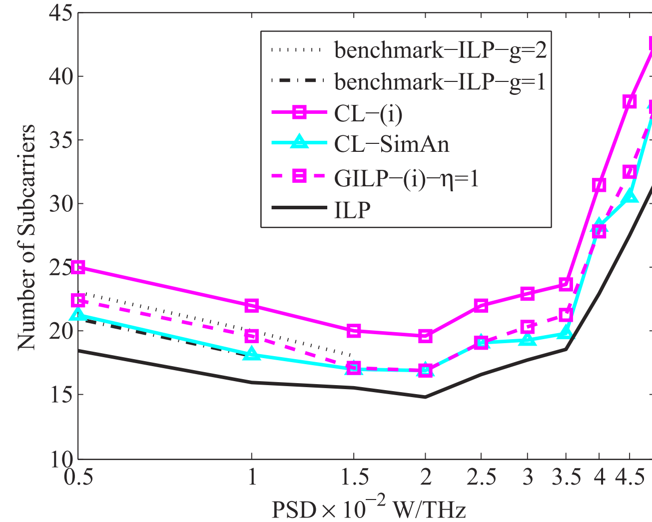


(a)

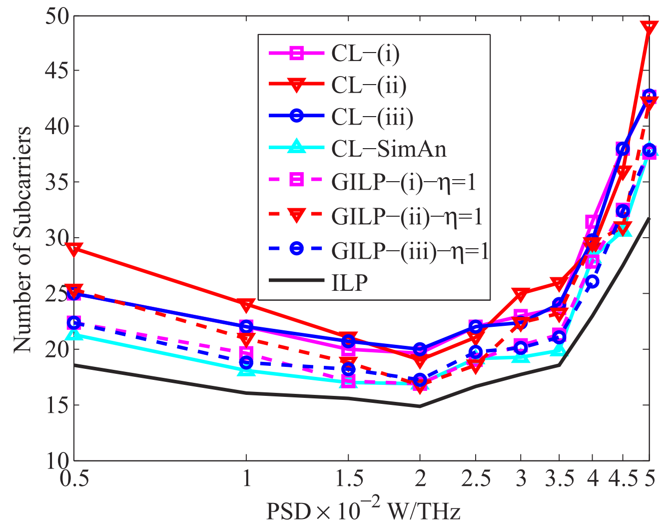


(b)

Fig. 6. The bandwidth (average of maximum allocated subcarrier indexes) versus PSD (see G in Table I) for the bit rate requirement of each connection is between 1250 and 3750 Gb/s in the six-node network with doubled link length. (a) Main algorithms compared with benchmarks. (b) Proposed algorithms, including the sorting policies.



(a)



(b)

Fig. 7. Bandwidth (average of maximum allocated subcarrier indexes) versus PSD (see G in Table I) for nonuniform traffic demands in the six-node network. (a) Main algorithms compared with benchmarks. (b) Proposed algorithms, including the sorting policies.

original link length, the NLI is increased, since it is proportional to the link length according to (2). The optimal ILP can save up to 22% subcarriers compared with the benchmark ILP of two subcarrier guardband when $G = 0.015$ W/THz.

When the bit rate requirement of each connection increases to the range between 1250 and 3750 Gb/s, the resulting bandwidths as a function of the PSD (see G in Table I) are shown in Fig. 5. The results confirm that when the value of PSD is high, the benchmark fails to provide feasible solutions. The ILP provides up to 19% bandwidth reduction (compared with the benchmark ILP with $g = 2$) when $G = 0.015$ W/THz. After scaling the network topology by doubling each link length, we get the results in Fig. 6.

Besides uniform traffic, we also consider a normalized traffic demand matrix used in [24]. The normalized traffic demand $\Lambda'_{s,d}$ for each pair of nodes s, d is calculated as (for $s \neq d$), $\Lambda'_{s,d} \propto \exp(Z_{sd}/Z^0)$, where Z^0 is a characteristic traffic distance and $Z_{s,d}$ is the length of shortest path between node s and node d. Demands are normalized by $\sum_{s,d} \Lambda'_{s,d} = 1$, and the actual traffic demand $\Lambda_{s,d} = Q\Lambda'_{s,d}$, where $Q = 5000$, $Z^0 = 1000\,\mathrm{km}$ are used in the simulation. The results are shown in Fig. 7. Again, when the value of PSD is high, the benchmark fails to provide feasible solutions. Furthermore, The ILP provides 13% bandwidth reduction (compared with the benchmark ILP with $g = 2$) when $G = 0.015$ W/THz.

C. Results for 14-node Network

The ILP and GILP are too time consuming to provide optimal results for the larger 14-node network[9]. so we only present

[9]The reason why GILP is time consuming is that for each value of E, if there is no feasible solution, then the heuristic will run again from the beginning, which results in many re-running of the GILP heuristic.

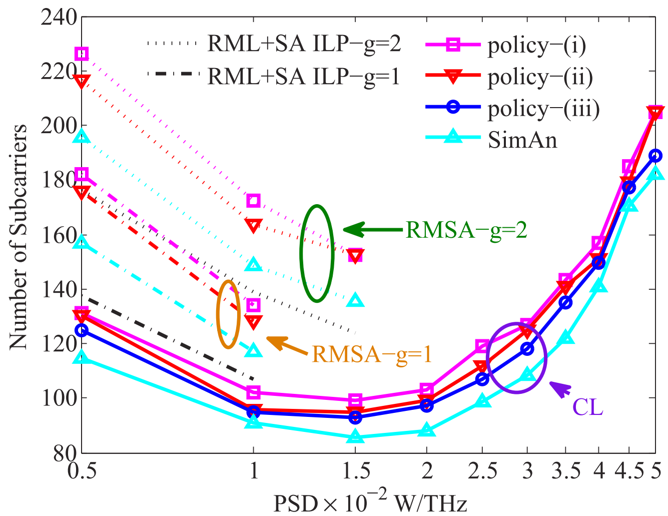


Fig. 8. Bandwidth (average of maximum allocated subcarrier indexes) versus PSD (see G in Table I) for the bit rate requirement of each connection is between 312.5 and 625 Gb/s in the 14-node DT network for benchmark and CL heuristic with policies (i), (ii), (iii), and simulated annealing.

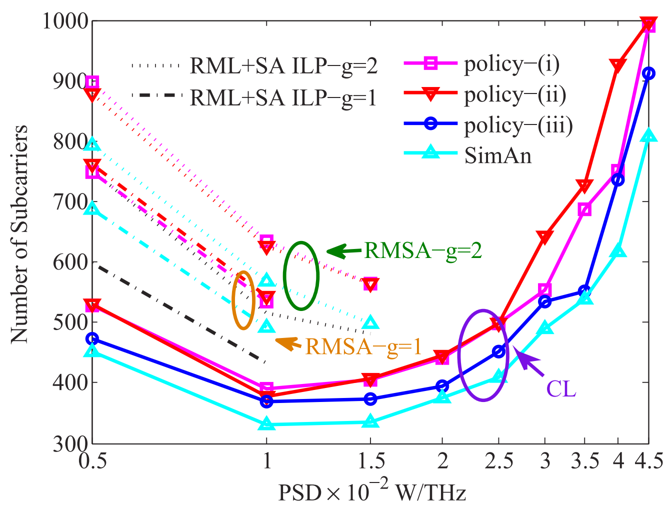


Fig. 9. Bandwidth (average of maximum allocated subcarrier indexes) versus PSD (G in Table I) for the bit rate requirement of each connection is between 1250 and 3750 Gb/s in the 14-node DT network for benchmark and CL heuristic with policies (i), (ii), (iii), and simulated annealing.

results of the proposed CL and benchmark heuristics RML+SA ILP (aborted after 4-hour simulation), the RMSA heuristic with two connection sorting policies (RMSA-(i) and RMSA-(ii)), and RMSA-SimAn.

In the case where the bit rate requirement of each connection is between 312.5 and 625 Gb/s, the results are shown in Fig. 8. Compared with RMSA-SimAn with $g = 2$, CL-SimAn can save up to 31% bandwidth when $G = 0.015$ W/THz. Also, the policies (ii) and (iii) have better performance than policy (i), which shows that the path distance is a more important factor than the number of required subcarriers in this case.

In the case where the bit rate requirement of each connection is between 1250 and 3750 Gb/s, the results are shown in Fig. 9. The results confirm that the benchmark heuristics provide feasible solutions only when PSD is low. CL-SimAn achieves up to 22% bandwidth reduction compared to the RMSA-SimAn with $g = 1$ when $G = 0.01$ W/THz. Also, CL-(iii) has better performance than CL-(i) and CL-(ii), since policy (iii) takes the bit rate requirement and the path distance into account.

V. Conclusion

In this paper, we investigated the nonlinear impairment aware routing and spectrum allocation problem in elastic networks based on NWDM and OOFDM. Simulation results indicate that, for the DT network, the proposed algorithms outperform transmission reach based state-of-the-art methods up to 31% in terms of bandwidth under low bit rate requirements and up to 22% under high bit rate requirements. Furthermore, the proposed ILP optimization achieves better performance for both uniform (up to 22% bandwidth reduction) and a non-uniform distribution (up to 13% bandwidth reduction) traffic demand in a 6-node network. In addition, it is shown that NLI should be considered in the optimization problem to guarantee the quality of transmission and avoid infeasible solutions. When the differences of link lengths and differences of bit rate requirements for connections are large, it is better to utilize a sorted connection allocation order which takes into account both bit rate requirement and path length. The simulation results also show that the optimum power spectrum density (the power spectrum density value that achieves the lowest bandwidth allocation) decreases as the link length in the network increases and as the bit rate requirement of each connection increases, since either of the increases results in more NLI.

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