Provisioning of dynamic traffic in mixed-line-rate optical networks with launch power determination

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Received: 28 July 2013 / Accepted: 4 April 2014 / Published online: 24 April 2014

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1 Introduction

Network operators are facing a continuous traffic increase both in terms of diversity of traffic demands and bandwidth. Such increase, mainly driven by new bandwidth-hungry services, requires migration of legacy 10G optical backbone networks toward higher (40G, 100G) line rates. Since it is impractical and perhaps even undesirable to upgrade all 10G transmission components to higher line rates at once, wavelength-division multiplexed (WDM) optical networks support mixed-line-rates (MLRs) to meet the requirements for capacity increase. MLR refers to an architecture where different line rates on different wavelengths can coexist on the same fiber. MLR architectures can be built over transpar-ent,[1] as well as translucent optical networks.[2]

1 In a transparent optical WDM network, transmitted signals remain in the optical domain along the entire path; thus, electronic signal process-ing is not needed at intermediate nodes.
2 Translucent networks employ signal regenerators at some nodes along the path [1].

Along a transparent optical path, a signal experiences various physical layer impairments (PLIs), and its quality degrades as it travels through several optical components [1]. A major impairment is the accumulated noise, mainly due to amplified spontaneous emission (ASE) and crosstalk (XT). Lightpaths are also affected by nonlinear impairments, such as self-phase modulation (SPM) and cross-phase modulation (XPM), which are the shifts in the phase of a signal caused by the change in intensity of the signals itself or on the neighboring wavelength, respectively. For 10G line rate, on-off keying (OOK) with direct detection is the most commonly used transmission technique. Higher line rates (e.g., 40G, 100G) require advanced modulation techniques, such as differential quadrature phase-shift keying (DQPSK) and dual-polarization quadrature phase-shift keying (DP-QPSK) [2]. DQPSK and DP-QPSK modulated signals are highly susceptible to PLIs. Moreover, coexistence of OOK signals with advanced modulation formats induces high XPM on phase-shift keying channels [3,4]. So, accounting for PLIs during the provisioning phase is an important problem in single-line-rate WDM networks (PLI-aware provisioning [5]) that acquires even larger importance in MLR networks.

In optical transmission, launch power is the one of the main parameters that affect the signal quality at the receiver side. Increasing the launch power results in higher resilience to noise, but it does not guarantee to improve the signal quality due to the nonlinear effects, i.e., the signal with high power would be distorted by fiber dispersion and fiber Kerr nonlinearity. Increasing the power of a signal also increases the linear and nonlinear crosstalk on neighboring wavelengths. Therefore, the quality of the signal at the receiver site of a transparent optical path is dependent on the launch powers of both the actual signal and the neighboring signals on the network.

In this study, we investigate the problem of launch power determination for dynamic connection provisioning. We propose two novel launch power determination algorithms aimed at maximizing the number of established connections. Our approaches consider the current state of the network and are PLI-aware. In worst-case best-case average (WBA), average value of optical reaches[3] is computed for worst- and best-cases and used for launch power determination. In worst-case, the impairments induced by other lightpaths are at the highest level, and in best-case, the actual lightpath is not affected by any other lightpath. In impairment-aware launch power determination (I-ALPD), impairments along the path are considered in a practical way to determine the launch power. The I-ALPD tracks the current state of the network and assigns weight values to the wavelengths according to the impairments. The I-ALPD determines the launch power of the lightpath dynamically by comparing the weights on the selected path wavelength with the weight thresholds. An auxiliary graph is used to capture the PLIs on each wavelength with a weight assignment scheme.

The rest of the paper is organized as follows. Previous studies related to the launch power determination problem are presented in Sect. 2. In Sect. 3, bit error rate (BER) evaluation model is given and the effects of launch power on overall network performance are discussed. The formal definition of the problem is given in Sect. 4, and we introduce two heuristic algorithms for dynamic launch power determination in Sect. 5 . Section 6 provides illustrative numerical examples. Finally, Sect. 7 concludes the paper.

2 Related works

Various studies have been reported on the impairment-aware dynamic lightpath establishment in MLR networks [7–12], but there are only a few studies on the launch power determination problem.

In [13], the authors propose a dynamic launch power control algorithm that adjusts the source power of certain channels upon the arrival of a new lightpath request. All source powers are allowed to be adjusted, even after the lightpaths have been admitted to the network. In the proposed model, all optical crossconnects (OXCs) communicate with a network management system (NMS) upon the arrival of a connection request. NMS starts the power adjustment procedure and decides whether to establish the lightpath with a minimum or a larger initial power. The power of a certain channel can be increased by raising the clamping levels of the equalizers on a part of its route, or on its entire route.

In [14], the authors use a global optimization algorithm to find the optimum launch powers and dispersion map of a single channel at various line rates.

In [15], the authors present a sensitivity study on how optical launch power can be managed to control the capital expenditure (CAPEX) of a MLR network. The authors investigate how the network cost (in terms of transceiver costs) varies with different traffic volumes to determine an optimal combination of launch powers that can lead to the lowest network cost. The cost of capacity follows volume discount[4] as the cost scales up nonlinearly with capacity. It is observed in the study that the network cost depends on traffic and power variation, i.e., if 10G lightpaths are established with lower launch powers, more volume discount can be exploited, as more high-bit-rate lightpaths can be accommodated.

In [16], the authors propose a dynamic launch power control algorithm for MLR networks. In order to guarantee acceptable quality of transmission (QoT), for each lightpath, appropriate launch power is determined dynamically.

[3] Reach is the distance an optical signal can travel before the signal quality degrades to a level that necessitates regeneration [6].

[4] The discount given to a customer who buys a large quantity of goods.

They also investigate the optimum launch power margin that helps to avoid QoT violations caused by interference of future requests. The algorithm searches for appropriate launch power sequentially, starting from minimum power value, until an acceptable BER is obtained.

In [17], the authors address the routing and wavelength assignment (RWA) problem from the energy consumption point of view considering a single-line-rate network. They investigate the optimum path and wavelength leading to minimum power consumption.

Our study is one of the few dealing with PLI-aware lightpath provisioning with launch power determination. We propose two practical and efficient approaches, which consider the current state of the impairments, and determine launch powers dynamically. As a launch power determination algorithm, our approaches make BER calculation only for the determined launch power, not for all possible launch power values. Thus, our approaches do not bring additional computational burden. The proposed approaches can also be adapted to different networks with different infrastructures.

3 Effects of launch power

3.1 BER estimation

In transparent WDM optical networks, the signal quality degrades due to PLIs along the path. The received signal quality at the destination node may be so poor that the BER can be unacceptably high. Therefore, we should evaluate the quality of the signal at the receiver side. Although exact evaluation of BER is not simple and can only be made via actual monitoring in electrical domain, for the purpose of this study, we can still estimate the signal quality using analytical approximation models [2].

The impairments can be classified into two categories according to their dependence on signal power: linear and nonlinear. The linear impairments are static in nature and are independent of the signal power. The nonlinear effects, on the other hand, are dynamic, and more complex to analyze [1].

A major impairment is the accumulated linear noise along the path. Optical signal-to-noise ratio (OSNR) is the ratio between the total signal power and the noise power on the reference bandwidth [18]:

$$\text{OSNR} = \frac{P_{\text{received}}}{N_{\text{linear}} + N_{\text{non-linear}}} \tag{1}$$

where, P_{received} denotes the signal power at the receiver, and N_{linear} and $N_{\text{non-linear}}$ denote the undesired linear and nonlinear noise power, accumulated along the path. It follows that launch power of the optical signal is a very critical parameter for QoT in WDM networks. Although increasing the launch power seems to be a simple way to ensure the QoT from Eq. (1), the launch power must be carefully increased due to the nonlinear impairments. The power must be large enough to provide an acceptable OSNR, but it must be below the limit where fiber nonlinearities distort the signal itself. In fact, on one hand, if the launch power is below the optimum value, accumulated noise along the path distorts the signal quality at the receiver side. On the other hand, if it is above the optimum value, fiber nonlinearities limit the quality of transmission.

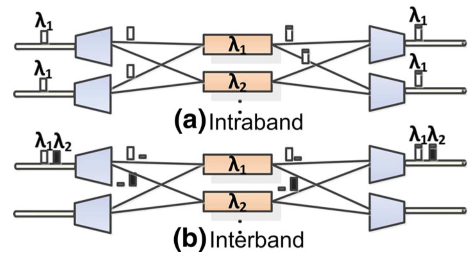

Fig. 1 Switch crosstalk types

The main source of the noise is the amplifier spontaneous emission (ASE), induced by in-line optical amplifiers. In this study, the accumulated effect of cascaded in-line amplifiers is considered in the calculation of OSNR according to [18]. Another source of the noise is the crosstalk (XT) caused by nonideal isolation of switch components. Two different types of switch crosstalk are considered in this study. In an OXC, lightpaths crossing the same node over the same wavelength incur intra-band crosstalk (Fig. 1a). Also, lightpaths on adjacent wavelengths coming from the same input of the OXC on adjacent wavelengths incur inter-band crosstalk (Fig. 1b) [19]. As the power of signal on a lightpath decreases along its path, so does the XT it causes.

Different light polarizations propagating in the same fiber at different speeds cause another type of dispersion called polarization mode dispersion (PMD). PMD randomly diminishes pulse height and broadens pulses. A Q-factor penalty is added for PMD as described in [20]. XPM and SPM are taken into account using the approximation given in [21].

MLR networks adopt different modulation schemes, and each modulation scheme requires a different BER evaluation model. BER estimation models according to different modulation formats are explained below.

3.1.1 On–off keying (OOK) systems

BER of a signal depends on Q-factor as [22]:

$$\text{BER} = \frac{1}{2}\text{erfc}\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp(-Q^2/2)}{Q\sqrt{2\pi}} \tag{2}$$

With Gaussian distribution of the intensity of impairments, the Q parameter is given as [21]:

$$Q = \frac{2\rho}{\sqrt{M} + \sqrt{M + 4\rho}} \quad (3)$$

where M is the receiver sensitivity given as $M = 2B_0T$ (B_0 is the optical filter bandwidth, and T is the symbol time). ρ is defined over OSNR as $\rho = nB_{\text{ref}}T \cdot \text{OSNR}$, where B_{ref} is the reference bandwidth, n is the ratio between number of noise and signal polarizations (e.g., for OOK and DQPSK systems, noise is assumed to affect both polarizations and one signal is transmitted, thus $n = 2$, and in DP-QPSK $n = 1$). The parameters used in BER evaluation models are given in Table 3.

3.1.2 *Quadrature phase-shift keying (QPSK) systems*

Different from OOK channels, signal quality of QPSK channels is highly susceptible to the XPM induced by neighboring OOK channels. In QPSK systems, an error occurs when the received signal phase is different from the transmitted one by more than $\pi/4$. With the assumption of phase noise being Gaussian, phase rotation induced by noise differs from a given angle (θ) approximately by $Q(\sqrt{2\rho}\sin\theta)$. Using this information, we can use the BER evaluation model given in Eq. (2), with the following formula for Q-factor [21]:

$$Q = \frac{\pi/4}{\sqrt{\frac{S}{2\rho}\left(\frac{\theta}{\sin\theta}\right)^2 + \sigma_{NL}^2}} \quad (4)$$

where S stands for affected symbols (1 and 2, for DQPSK and DP-QPSK, respectively) and $\theta = (\pi/4)/(S + 2\rho\sigma_{NL}^2)$.

The variance of nonlinear phase noise has two components: SPM and XPM variances ($\sigma_{\text{NL}}^2 = \sigma_{\text{SPM}}^2 + \sigma_{\text{XPM}}^2$). These noise variances are approximated differently for DQPSK and DP-QPSK systems. For DQPSK, SPM contribution of phase noise variance is calculated according to: $\sigma_{\text{SPM}}^2 \approx 4\phi_{\text{SPM}}^2/(3\rho)$; while in *DP-QPSK*, variance of SPM noise is approximated as: $\sigma_{\text{SPM}}^2 \approx 2\phi_{\text{SPM}}^2/(3\rho)$. ϕ_{SPM} is the optical phase shift due to SPM effect. Variance of XPM, σ_{XPM}^2, is calculated according to the model given in [21]. Guard band (GB) is defined as the minimum number of wavelengths between a phase-shift keying channel and an OOK channel after which XPM effects can be negliged for BER calculation. The GB value is evaluated as in [21].

Increasing the power of a signal also increases the linear (i.e., inter- and intraband) and nonlinear crosstalk (i.e., XPM and FWM) on neighboring wavelengths. Higher launch power also induces interchannel crosstalk (i.e., XPM and FWM) that disrupts the neighboring signals. 100G channels are highly susceptible to launch power of neighboring channels, and they suffer from XPM and linear crosstalk effects of co-propagating 10G channels [4,23]. Adjacent 40G channels cause lower penalties because of the shape of the multiplexer filters [24]. The performance of 40G channels is also degraded by both XPM and linear crosstalk effects [25,26]. Thus, not only the launch power of the actual signal, but also the launch powers of neighboring lightpaths affect the quality of optical transmission.

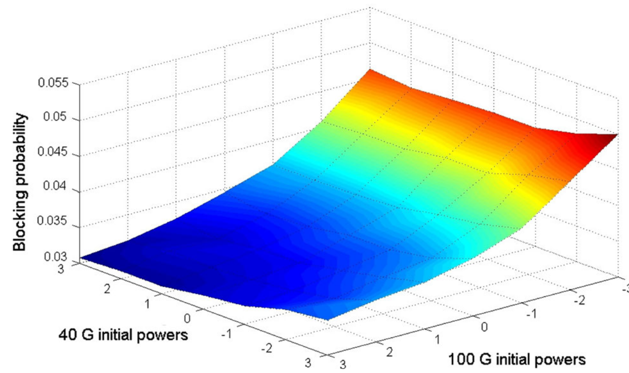

Fig. 2 Blocking probability change according to launch power variation

3.2 Launch power effect

The effect of the launch power, using the BER evaluation model given above, is examined through a preliminary study. In this preliminary study, lightpath provisioning performance of different launch powers (discrete values between −3 and 3 dBm) for different line rates (10G, 40G, and 100G) is evaluated. For each run of the simulation, launch power of a single-line rate is altered while launch power of the others is kept the same. Shortest-path, first fit (SP-FF[5]) is used to evaluate the performance of algorithms. Same amount of traffic load (≈50 % utilization) is offered to the network for each run of the simulation.

The results of the study indicate that increasing the launch power increases the resilience to noise and gives better performance. On the other hand, increasing the launch power of a line rate decreases the lightpath provisioning performance of the other line rates. DP-QPSK modulated channels with 100G line rate are highly susceptible to launch power of neighboring lightpaths, especially OOK-modulated 10G line rate channels. From blocking probability perspective, the best performing (inducing minimum blocking ratio) combination of initial powers is obtained as −2, 0, 2 dBm for 10G, 40G, and 100G, respectively. Worst performing launch power combination, in terms of blocking probability and system throughput, is obtained as 2, −3, −3 dBm for 10G, 40G, and 100G, respectively. Figure 2 shows the blocking ratio of two different line rates (40G and 100G) with different launch powers on NSFNET (Fig. 4a). In Fig. 2, launch powers of 10G lightpaths are kept fixed (0 dBm) during simula-

[5] SP-FF chooses the first available wavelength on shortest-path.

tion, and launch powers of 40G and 100G are altered from −3 to 3 dBm.

The results of this preliminary study and the other studies in the literature indicate that detrimental effects of PLIs induced by neighboring lightpaths can be significantly reduced by carefully choosing appropriate launch powers. PLI-aware approaches are needed to determine the launch power of lightpaths in MLR networks. Due to the dynamic nature of lightpath provisioning, the proposed approaches should be dynamic and easy to implement.

4 Problem definition

In this study, we investigate the problem of impairment-aware dynamic lightpath provisioning with launch power determination. PLIs and the current state of the network are considered. The problem can be formally stated as follows:

Given:

- A dynamic connection request with a given rate to be established on the network,
- Physical topology,
- Number of wavelengths carried by each fiber,
- Current state of the network, and
- Impairment parameters.

The goal was to determine:

- Route over which the lightpath should be set up,
- Wavelength to be assigned, and
- Launch power to establish the lightpath for the requested connection,

The objective of the problem was to maximize the number of established connections while satisfying the given BER for an incoming connection, and to avoid disrupting existing lightpaths. Specifically, we deal with launch power determination in this study.

5 Proposed algorithms

In this study, we propose two different algorithms to determine the launch power of a lightpath for impairment-aware provisioning in MLR networks. In the WBA, optical reach for highest possible impairment (worst-case) and without impairment (best-case) scenarios are used to determine the launch power. In the I-ALPD, current state of impairments along the path is considered to determine the power value. Details of the algorithms are discussed below.

5.1 Worst-case best-case average (WBA)

WBA scheme takes impairments into consideration in an average manner. It calculates the optical reaches for best and worst conditions, in terms of impairments, and uses the average of reach values to compare with the length of the candidate lightpath. For 40G (and 100G), worst-case scenario occurs when the central wavelength is occupied by the 40G (or 100G) signal while all the other wavelengths are occupied by 10G OOK signals, along the path. In worst-case scenario, the neighboring OOK signals have the highest possible launch power (i.e., 3 dBm). For OOK signals in worst-case scenario, neighboring wavelengths are occupied with signals having the highest possible launch power. Best-case scenario is same for all line rates, i.e., the network is empty. This approach provides a simple approximation for medium loaded networks. It is easy to implement, and it does not bring computational burden. The WBA algorithm is given in Algorithm 1.

Algorithm 1 WBA algorithm.

1. Prior to any connection request, find the optical reaches for worst- and best-cases, and constitute an average-reach table. After a connection request comes, and RWA algorithm finds a candidate lightpath.
2. Get the length of the candidate lightpath.
3. Look up the average-reach table to find the appropriate power.
   - Go down to the requested line rate.
   - Search for the closest reach value to the lightpath length in this row.
   - Select the matching power value.
4. If the candidate lightpath is accepted after BER evaluation, establish lightpath.

Before any request comes, the reaches for both (worst, best) cases are calculated for each launch power value (i.e., −3 to 3 dBm). The average of best- and worst-cases is calculated, and these average reach ($R_a^{P_{ch}}$) values are kept in a table (i.e., Table 1). When a request comes, first the RWA algorithm finds a path from source s to destination d, and then, WBA determines the launch power. In WBA, starting from the minimum power option (P_{ch}(Min)), the differences between path length and average reach are examined, and the power value having the minimum difference between average reach and path length is selected:

$$\mathrm{Min}_{P_{ch}(\mathrm{Min-Max})}\Big(\mid L_{sd} - R_a^{P_{ch}} \mid \qquad (5)$$

where L_{sd} is the length of the path, and $R_a^{P_{ch}}$ is the average-reach with launch power P_{ch}.

The algorithm examines the average reach values sequentially and finds the closest one to the path length, i.e., for a connection request with 40G line rate, let the length of the path from s to d be 2,100 km. Given Table 1, since the path-length average-reach difference for −2 dBm (|2,000−2,100|) is smaller than the difference for other power values (i.e., for −1 dBm |2,500−2,100|), −2 dBm is selected.

WBA algorithm constitutes the reach table before any request comes, and it starts working after the candidate lightpath is found. Apart from RWA algorithm, let P be the number of available launch powers, and R be the number of line rates, then finding the appropriate launch power from the average-reach table has $O(R+P)$ complexity.

5.2 Impairment-aware launch power determination (I-ALPD)

The I-ALPD algorithm keeps track of impairments on each wavelength-link and assigns weight values to the wavelengths according to the impairments. The algorithm uses an auxiliary graph $G(V, E)$ (Fig. 3), to keep track of the current state of impairments. According to the total weight accumulated along the path on the selected wavelength, I-ALPD determines the launch power of lightpaths. The weight assignment process can be made off-line, using the idle time between dynamic connection requests.

5.2.1 Auxiliary graph construction

To construct the auxiliary graph $G(V, E)$, we first replicate the physical nodes (V_0) as the number of line rates. The ith vertex of the auxiliary graph (Fig. 3a) is denoted by $\{V_0^i, V_1^i, \ldots, V_k^i, \ldots, V_R^i\}$, where R is the number of line rates.

Then, the physical links ($E_0^{i,j}$) connecting nodes (V_0^i, V_0^j) are replicated. The links of the new graph (Fig. 3b) are denoted by $\{E_0^{i,j}, E_1^{i,j}, \ldots, E_k^{i,j}, \ldots, E_R^{i,j}\}$.

Each wavelength on a link is considered separately and associated with a weight value ($W_{i,j,k}^{\lambda}$), which is assigned according to the current state of the network (Fig. 3c). This weight value represents the propagation penalty of transmitting the signal over a specific wavelength (λ) on that physical link (i, j) with specific line rate (k).

The weight values are initialized before any connection request arrives, according to linear impairments (ASE, losses, and PMD). After each lightpath is established or released, the weight values are recalculated along the path ($s-d$) for the wavelengths within the GB of the newly-established lightpath. The weight values are calculated as discussed below.

5.2.2 Weight assignment

The weight values represent linear and nonlinear impairments that occur on the physical links (ASE, losses, and SPM), and on the nodes (XT and losses). Unlike OOK-modulated channels, DQPSK and DP-QPSK channels are also affected by the intensity variations in neighboring channels. XPM effect of OOK signals on DQPSK and DP-QPSK channels is taken into account for the lightpaths within the GB. Weight assignment at nodes and links are as follows.

Weight assignment for a vertex: The weight of a node represents the propagation penalty due to crosstalk within that node. Two different types of switch crosstalks (inter- and intraband crosstalk, see Sect. 3.1) are considered in this study.

Each vertex j of the auxiliary graph is assigned a weight value ($W_{V_k^j}^{\lambda}$) for each wavelength of the input/output port, where k is the requested line rate. Let N be the number of ports (input/output) of each node, then crosstalk values at node V_k^j on wavelength λ are taken into account as vertex weight value ($W_{V_k^j}^{\lambda}$) as follows:

$$W_{V_k^j}^{\lambda} = \omega_{XT_a}^{\lambda}.\nu_{XT_a}^{j,\lambda\mp 1} + \sum_{p=1}^{N} \omega_{XT_b}^{\lambda}.\nu_{XT_b}^{j,\lambda,p} + \kappa \quad (6)$$

where $\omega_{XT_a}^{\lambda}$ and $\omega_{XT_b}^{\lambda}$ indicate the predefined weight factors of the crosstalk components; $\nu_{XT_a}^{j,\lambda\mp 1}$ and $\nu_{XT_b}^{j,\lambda,p}$ are the binary variables indicating the presence of a lightpath causing crosstalk on port p of node j on wavelength λ; and κ is the adjusting weight value indicating the losses caused by the taps, demultiplexers, switching elements, and multiplexers inside the node.

The weight caused by node j is accounted with the link i, j for specific wavelength λ.

Weight assignment for a link: Each wavelength (λ) on the edge ($E_k^{i,j}$) of the graph ($G(V, E)$) is assigned a weight value $W_{i,j,k}^{\lambda}$. The initial weight values are calculated considering ASE and SPM using Eq. (7). The weight values of the affected wavelengths of the links along the path are recalculated each time a lightpath is established or released.

Each link weight value encompasses various impairments and dynamically changes according to XT and XPM. The XT effect of the established lightpath is evaluated using Eq. (6). The wavelengths (λ_d) within guard band (∓GB) are added a weight value for XPM effect, depending on their distances ($|\lambda_n - \lambda_d|$) to the lightpath established on λ_n. The XPM effect decreases with the ratio of $\frac{1}{(\Delta\lambda)^2}$ [21], where $\Delta\lambda$ gives the number of wavelengths between affecting signal and the actual signal. Specifically, we define the weight assignment scheme for a wavelength (λ_d) at bit rate k on a link ($E_k^{i,j}$) in Eq. (7).

Table 1 Sample average reach table

Line rate	Average-reach (km)						
	−3	−2	−1	0	1	2	3 (dBm)
10G	2,200	2,800	3,200	3,600	4,100	4,200	4,200
40G	1,500	2,000	2,500	3,000	3,500	4,000	4,000
100G	800	1,000	1,200	1,400	1,600	1,800	1,800

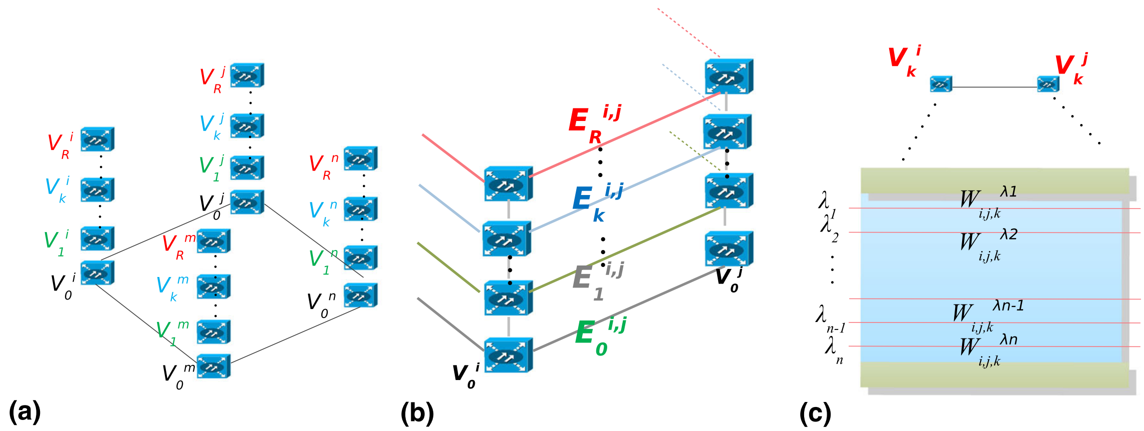

Fig. 3 Auxiliary graph construction. **a** Physical nodes are replicated. **b** Physical links are replicated. **c** Each wavelength on a link associated with a weight value

$$W^{\lambda_d}_{i,j,k} = W^{\lambda_d}_{V^j_k} + m.\omega^{\lambda}_{ASE} + \omega^{\lambda}_{SPM} + \sum_{k=1}^{R} \sum_{g=\lambda_n-GB}^{\lambda_n+GB} \frac{1}{(\Delta\lambda)^2} \omega^{k}_{XPM} \cdot \nu^{i,j,k}_{g} + \zeta \qquad (7)$$

where m is the number of spans within the link; R is the number of line rates; $\omega^{\lambda}_{\text{ASE}}$, $\omega^{\lambda}_{\text{SPM}}$, and ω^{k}_{XPM} are the predefined weight factors of ASE, SPM, and XPM, respectively. These values are assigned considering their effects on BER. These factors can be static, or they can be changed in time. $\nu^{i,j,k}_{g}$ denotes the existence of affecting lightpaths on link i, j with rate k on wavelength g, and ζ stands for the adjusting weight value for other impairments. The parameters used in link weight evaluation are given in Table 3.

Weights increased due to lightpath establishment are decreased when the lightpath is released (inverse update).

5.2.3 Algorithm

In I-ALPD, launch power is determined according to accumulated impairments along the selected path. Impairments on the network are tracked using the auxiliary weight graph. After finding the appropriate path and wavelength from source to destination, the total weight on this path is calculated. I-ALPD algorithm is given in Algorithm 2.

Total weight thresholds (i.e., Table 2) are used to determine the launch power of the lightpath. The algorithm examines the weight thresholds and finds the closest one to the total weight on the selected path, i.e., for a connection request with 40G line rate, let the weight on selected path from s to d be 0.5. Since $|0.4-0.5| < |0.7-0.5|$, -1 dBm is selected.

Algorithm 2 I-ALPD algorithm.

1. Update the auxiliary graph according to existing lightpaths.
2. Calculate the total weight on candidate lightpath.
3. Look up the thresholds table to find the appropriate power.
   - Go down to the requested line rate.
   - Search for the closest threshold value in this row.
   - Select the matching power value.
4. If the candidate lightpath is accepted after BER evaluation,
   - Establish the lightpath.
   - Update the auxiliary graph.

I-ALPD algorithm calculates the total weight along the path in linear time, $O(E_{\text{LP}})$, where E_{LP} denotes the edges of the candidate lightpath. Since weight caused by vertex j is accounted with the edge i,j for specific wavelength λ, only edge weights are considered. Let P be the number of available launch powers, and R be the number of line rates, then finding the appropriate launch power from the weight threshold table has $O(R+P)$ complexity. The main computational burden of this algorithm is to update the auxiliary graph with complexity of $O((2 \times \text{GB} \times R \times E_{\text{LP}}) + (N \times V_{\text{LP}}))$, where $2 \times$ GB denotes the affected wavelengths, and N denotes the number of ports at each vertex. On the other

Table 2 Sample weight thresholds

Line rate	Weight thresholds						
	−3	−2	−1	0	1	2	3 (dBm)
10G	0	0.5	1	2	3	4	5
40G	0	0.2	0.4	0.7	1	2	3
100G	0	0.1	0.2	0.4	0.6	0.8	1

hand, auxiliary graph, which is referred for online connection requests, is updated off-line, after a lightpath is established or released.

6 Illustrative numerical examples

In this study, we consider an optical WDM network in which each node can support transmission at 10, 40, and 100 Gbps. Different topologies, NSFNET with 14 node and 21 links (Fig. 4a), and the European Optical Network (EON) with 28 nodes and 41 links (Fig. 4b) are used to evaluate the performance of the proposed schemes. EON has shorter link distances (average ≈550 km) than NSFNET (average ≈930 km). In our network model, all nodes are assumed to have adjusting launch power capability, but power sources are not allowed to be adjusted after establishing the lightpaths. Physical links are assumed to have inline (EDFA) amplifiers at every 82 km, with 70 km standard single-mode fiber, and 12 km dispersion compensation fiber. We considered 50 GHz spacing with 80 wavelengths.

Least congested path (LCP)-first fit (FF) is used to find the appropriate path and wavelength. The LCP method is a modified version of LCP algorithm introduced in [27]. The algorithm first finds n-shortest paths [28], and then selects the path that has the maximum number of available wavelengths. FF selects the first available wavelength on the selected path. Wavelength continuity constraint is applied for intermediate nodes. Launch power of this candidate lightpath is determined using one of the launch power determination algorithms. BER evaluation is made to see whether the candidate lightpath meets the minimum BER requirement with the selected launch power. Signal quality of the existing lightpaths, which would be affected from the candidate lightpath, is examined before establishing the new lightpath. If the candidate lightpath distorts the signal quality of any existing lightpath to have unacceptable BER value, the lightpath is not established, and the connection request is rejected.

The connection requests arrive according to Poisson distribution with exponentially distributed holding times, and they are uniformly chosen among 10G, 40G, and 100G. The traffic load is given in Erlangs. We run the simulations for one million connection requests. Discrete values from −3 to 3 dBm are used for launch powers. Other system parameters are given in Table 3.

To construct the table, we searched the distance space sequentially for best- and worst-cases, whether it has acceptable BER with given power value or not. The weight values used in this study (Table 3) are obtained from our previous study [11]. These weight values are parameters to implement the proposed algorithm and can be modified according to network operators' hardware and infrastructure. We used the same parameters for both topologies.

We compared our approaches with existing dynamic and fixed power approaches. Dynamic power control (DPC) is a dynamic I-ALPD approach, which is a modified version of the algorithm proposed in [16]. DPC searches for appropriate launch power sequentially starting with the possible minimum launch power, which is −3 dBm in this study. If the given launch power is not sufficient to establish a lightpath, the algorithm increases the launch power by minimum unit. This search goes up to maximum allowed launch power, which is 3 dBm in this study. The search ends with either finding the appropriate launch power for the lightpath or reaching the maximum allowed launch power. We also compared our approaches with fixed launch power (FLP) approach, where launch powers are fixed for all lightpaths. We used 0 dBm for FLP, which is the median of power values (−3 to 3 dBm) used in this study.

An incoming request can be rejected due to insufficient network resources (*resource blocking*) or to PLIs (*physical layer blocking*) [1]. LCP-FF algorithm finds an appropriate path and wavelength first. If the algorithm cannot find an appropriate path-wavelength pair, then the connection request is rejected due to resource blocking. After finding an appropriate path-wavelength pair, the candidate lightpath is evaluated for signal quality using the BER estimation model given in Sect. 3.1. If the signal quality is not good enough to establish this lightpath, then the connection request is rejected due to physical layer blocking. We evaluated the physical layer blocking performance of the algorithms separately to study the effects of launch power.

Figure 5 shows the blocking ratio due to PLIs for NSFNET; the blocking ratio due to insufficient network resources is not shown in this figure. Impairments induced by established lightpaths increase in parallel with increasing traffic load; thus, the physical layer blocking ratio increases for all algorithms. For medium and high traffic loads, resource blocking becomes higher (see also Fig. 7), and blocking ratio due to PLIs decreases (see also Fig. 6).

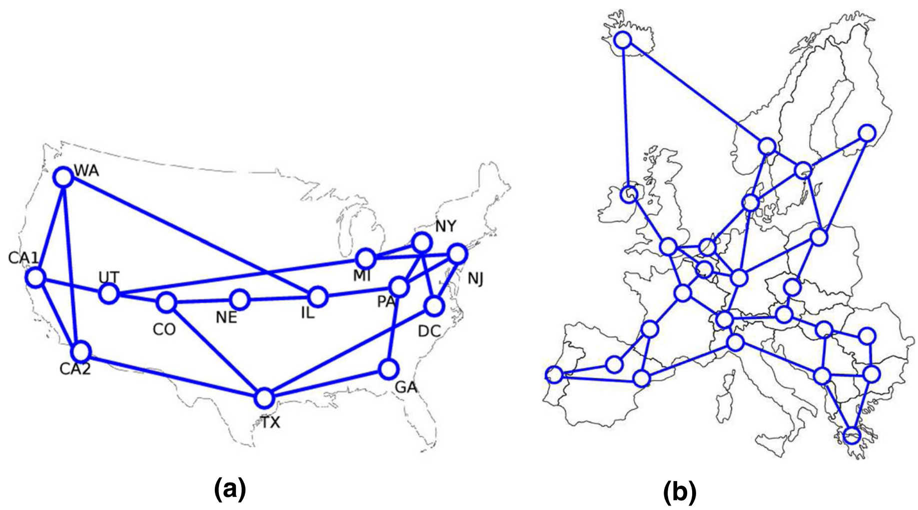

Fig. 4 Topologies used for performance evaluation. **a** NSFNET. **b** EON topology

Table 3 System parameters

Parameters	Value
Number of nodes, V, (NSFNET, EON)	14, 28
Number of edges, E, (NSFNET, EON)	21, 41
Number of wavelengths, W	80
Line rates (Gbps), ($R = 3$)	10, 40, 100
BER threshold	10^{-5}
B_{ref} (GHz)	12.5
Gain of EDFA ($G_{\text{in}}, G_{\text{out}}$) (dB)	20.8, 19
Amplifier noise factor (F) (dB)	4
Fiber loss factor, $\alpha_{\text{SMF}}, \alpha_{\text{DCF}}$(dB/km)	0.2, 0.6
Dispersion, $D_{\text{SMF}}, D_{\text{DCF}}$ ps/(km.nm)	17, 92
PMD Coefficient, $D_{\text{PMD}}\text{ps}/\sqrt{\text{km}}$	0.2
$L_{\text{SW}}, L_{\text{DMX}}, L_{\text{MX}}, L_{\text{tap}}$ (dB)	5, 5.5, 4.5, 1
$X_{\text{SW}}, X_{\text{DMX}}, X_{\text{MX}}$ (dB)	−60, −40, −40
Symbol time (10, 40, 100) (ps)	100, 50, 40
Kerr coefficient, n_2 (m^2/W)	3
$A_{\text{eff}}\, SMF, A_{\text{eff}}\, DCF$ (μm^2)	80, 30
Filtering effect ($K_{\text{DQPSK}}, K_{\text{QPSK}}$)	1, 7
$\omega^{\lambda}_{\text{XT}_a}, \omega^{\lambda}_{\text{XT}_b}$	0.05, 0.025
$\omega^{\lambda}_{\text{SPM}}, \omega^{k}_{\text{XPM}}$	0.1, 0.5
$\omega^{\lambda}_{\text{ASE}}$	1
κ, ζ	0.01, 0.5

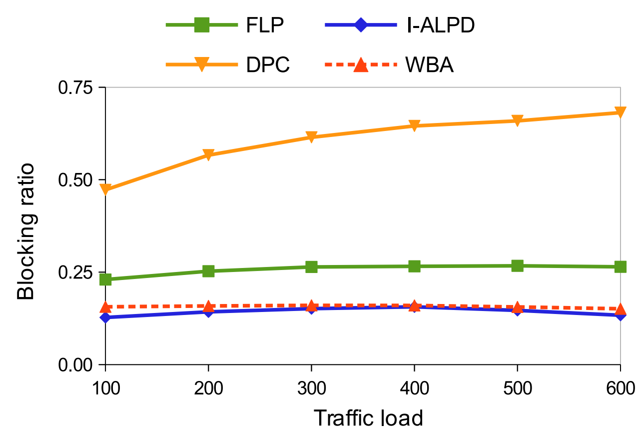

Fig. 5 Blocking ratio due to PLIs (NSFNET)

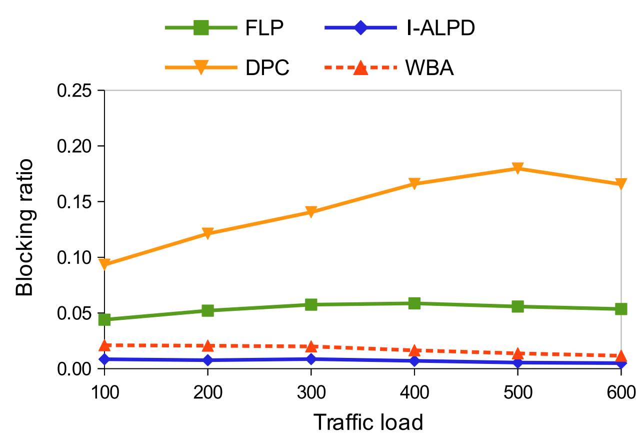

Fig. 6 Blocking ratio due to PLIs (EON topology)

The proposed algorithms show better blocking probability performance than the others. I-ALPD gives better results than WBA. DPC method has more blocking ratio than others. There are two main reasons for high blocking ratio of DPC. The first reason is the lightpaths established with high launch powers. DPC tries to establish each lightpath with minimum required launch power, but the search can go up to maximum allowed launch power. Each lightpath with high launch power, especially the OOK channels, affects other lightpaths and degrades the overall performance. The other reason is that the candidate lightpaths are not allowed to be established if they disrupt the existing lightpaths.

Figure 6 shows the blocking ratio due to PLIs for EON topology. EON has shorter link distances than NSFNET;

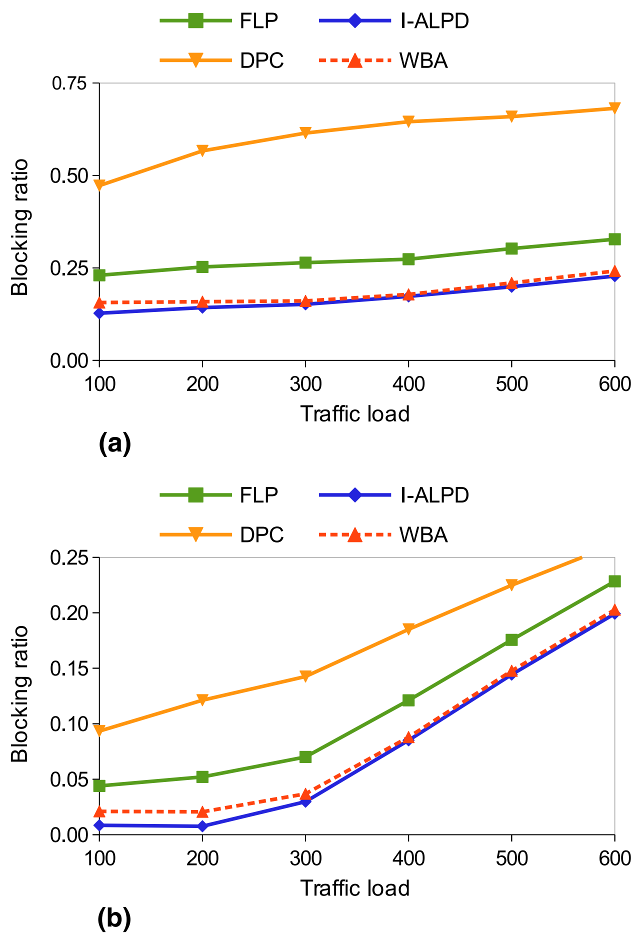

Fig. 7 Total (physical layer and resource) blocking ratio of proposed schemes for different topologies. **a** NSFNET. **b** EON topology

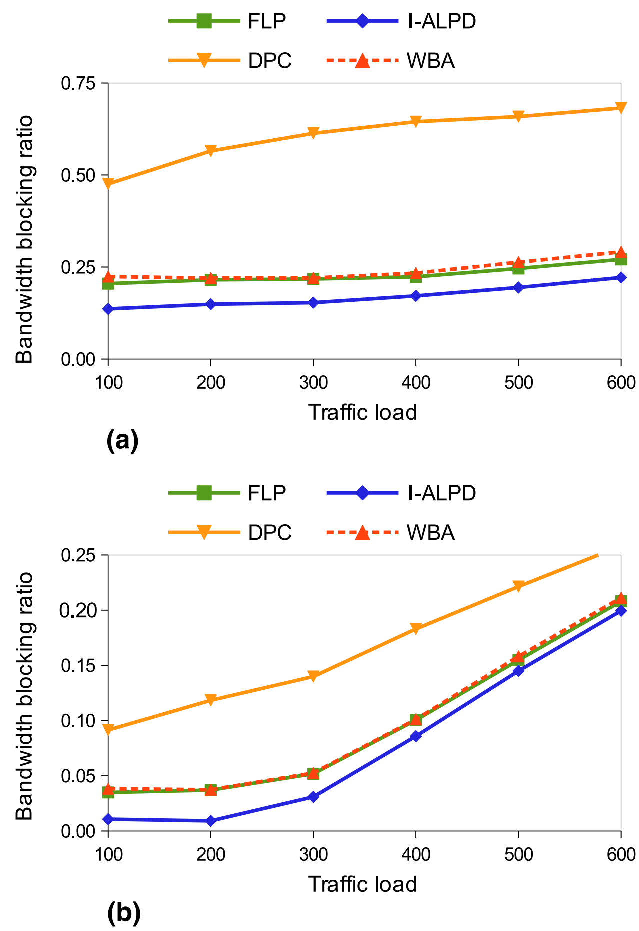

Fig. 8 Bandwidth blocking ratio of proposed schemes for different topologies. **a** NSFNET. **b** EON topology

thus, the blocking ratio due to PLIs for EON is lower than for NSFNET. On the other hand, EON has more number of nodes than NSFNET, with less average node degree, which causes the average hop count being higher than NSFNET. EON has also smaller connectivity than NSFNET. Increasing average hop count of paths increases linear XT, on the other hand, increasing average hop count in this topology decreases the network resources in terms of wavelength-links; thus, resource blocking becomes higher for medium and high traffic loads (see also Fig. 7), and blocking ratio due to PLIs decreases. I-ALPD experiences lower blocking probability than others. The blocking ratio differs with this topology but the performance of the algorithms does not change.

Figure 7 shows the total (physical layer and resource) blocking ratio for different schemes for different topologies. Again, I-ALPD experiences lower blocking probability than the other approaches for both topologies. WBA shows better performance than both FLP and DPC. The performances get closer with increasing traffic load. This is because resource blocking becomes the higher than physical layer blocking when the network utilization gets higher.

BBR is defined as the amount of bandwidth blocked over the amount of bandwidth offered [29]. Figure 8 shows the BBR for different lightpath provisioning schemes with uniformly distributed traffic. The algorithms show similar performances with total blocking ratio performance for both topologies. I-ALPD experiences lower bandwidth blocking ratio than the other approaches. In I-ALPD, weight threshold values for each line rate are different, and it helps to give priority for higher line rate. The performances of WBA and FLP are close to each other for all traffic loads, and they have the average performances. Increasing impairments decrease the performance of WBA, because WBA is based on the average value, which can be considered as the equivalent of medium traffic load.

The algorithms FLP, WBA, and I-ALPD make BER calculations only once for each connection request. If the obtained BER is acceptable, then the lightpath is established. In DPC, BER estimation can be made more than once for different launch powers. To evaluate the computational burden of the algorithms, we monitored the BER calculation of algorithms.

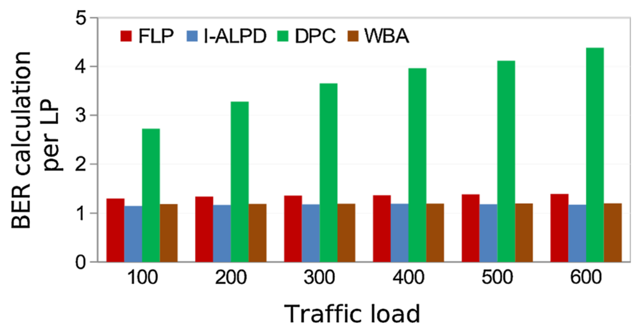

Fig. 9 BER calculation per lightpath

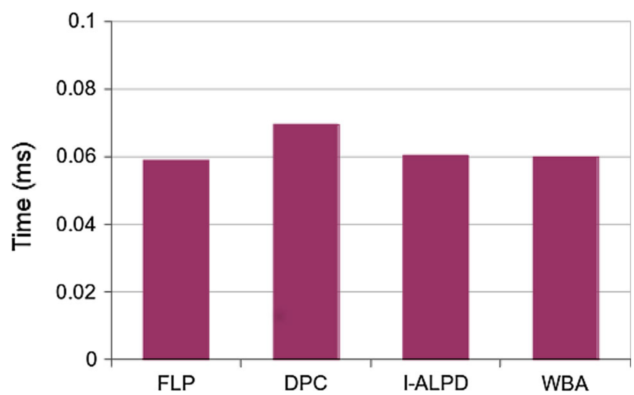

Fig. 10 Simulation time per connection request

Figure 9 shows the average BER calculations to establish a single lightpath. The results are obtained by dividing the number of BER calculations to number of lightpaths.

The differences between FLP, WBA, and I-ALPD are not significant, but DPC makes two or more times more BER calculation than the other algorithms per connection request. Number of BER calculations per connection request increases with increasing utilization for DPC.

Simulation times for algorithms show that FLP takes less time than others. Figure 10 shows the average time consumption of algorithms for one connection request in the same simulation environment. DPC spends more time than others, and I-ALPD and WBA take slightly more time than FLP. I-ALPD can use idle times between connection requests to update the auxiliary graph, but this figure includes the weight assignment times as well.

7 Conclusion

Signal quality at the receiver side of a transparent optical path depends on many factors, including launch power of the actual signal, neighboring signals, modulation technique, path length. In this study, we examined the effects of launch power on the signal quality in optical MLR networks. The effects of the launch power cannot be isolated from other parameters, but the performance in terms of blocking ratio can be improved by selecting appropriate launch powers.

We proposed two heuristic approaches to select the appropriate launch power for dynamic connection requests: WBA and I-ALPD. To determine the appropriate launch power, WBA uses the optical reach for highest possible impairment (worst-case) and without impairment (best-case) scenarios. I-ALPD considers the instantaneous state of the network and assigns weight values to the wavelengths in accordance with the impairments. By comparing the weights on the selected path-wavelength with the weight thresholds, I-ALPD determines the launch power of the lightpath dynamically. The proposed algorithms are evaluated through simulations and compared with dynamic power control and fixed launch power approaches. Our results indicate that I-ALPD outperforms the other approaches, in terms of blocking probability and bandwidth blocking ratio. We observed that the network performance, in terms of blocking probability, can be improved by selecting appropriate launch powers for lightpaths, considering the current state of the network.

Acknowledgments This study is partly supported by The Scientific and Technology Research Council of Turkey.

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