Impairment-aware dynamic lightpath provisioning in mixed-line-rate networks[☆]

Haydar Cukurtepe[a,*], Massimo Tornatore[b], Aysegul Yayimli[a],
Biswanath Mukherjee[c]

[a] Istanbul Technical University, Istanbul, Turkey
[b] Politecnico di Milano, Italy
[c] University of California, Davis, USA

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1. Introduction

Network operators are experiencing a continuous increase in terms of diversity of both traffic demands and bandwidth due to new services and bandwidth-consuming applications on the Internet. This increase is driving the migration from legacy (10G) optical backbone networks to 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 (MLR) 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 transparent, as well as translucent or opaque optical networks. In opaque networks, data transmission occurs over point-to-point

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[*] Corresponding author.

E-mail addresses: cukurtepe@itu.edu.tr (H. Cukurtepe), tornator@elet.polimi.it (M. Tornatore), gencata@itu.edu.tr (A. Yayimli), mukherjee@cs.ucdavis.edu (B. Mukherjee).

links so that the signal is regenerated at every intermediate node along transmission channel. The regeneration of optical signal is done using optical-electronic-optical (OEO) conversion. In translucent architecture, regenerators are placed sparsely. It eliminates much of the electronic process and allows a signal to remain in the optical domain as much as it can. In transparent networks, OEO conversions are not used at the intermediate nodes. The transmission occurs in optical domain. The optical channels cannot be processed at intermediate nodes on optical level but can be switched. Along the transparent optical path, a signal undergoes a number of physical-layer impairments (PLI) 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). Optical transmission channels are also affected by non-linear 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 wavelengths, respectively.

For 10G line rate signals, on-off keying (OOK) with direct detection is the most commonly used transmission technique [2]. Higher bandwidth results in a linear increase in noise level of the intensity-modulated channel. Thus, higher line rates (e.g., 40G and 100G) require advanced modulation techniques such as differential quadrature phase shift keying (DQPSK) and dual-polarization quadrature phase shift keying (DP-QPSK). DQPSK and DP-QPSK modulated signals are highly susceptible to PLIs; therefore, we have to take into account the trade-off between capacity and optical signal quality. Moreover, in MLR networks, coexistence of the OOK signals with the advanced modulation formats induces higher XPM [3,4], with respect to single-line-rate (SLR) systems. Accounting for PLIs during the provisioning phase, which is an important problem in SLR WDM networks [5] acquires even larger importance in MLR networks. In MLR networks, the problem has two additional dimensions: the disruptive interaction of different modulation formats, and the trade-off between capacity and optical reach.[1]

In dynamic traffic scenario, a connection request comes to the network, stays for a while, and terminates. Finding an appropriate route and assigning a wavelength to a given connection request is called the Routing and Wavelength Assignment (RWA) problem. Lightpath provisioning, in addition to RWA, deals with connection management and quality of signal. In this study, we propose two approaches for impairment-aware lightpath provisioning in MLR networks for dynamic connection requests. The first scheme, Fixed Wavelength-Interval Allocation (FWIA), partitions the wavelengths into groups, assigns each group to a different line rate, and establishes lightpaths with different modulation formats over the assigned wavelength groups. The second algorithm is the Weighted Routing and Wavelength Assignment (W-RWA) scheme, which captures the instantaneous state of the network and assigns weight values according to affecting impairments. The algorithm uses an auxiliary graph to track the effects of PLIs on each channel with a weight-assignment scheme. The algorithm selects the wavelengths which are less exposed to impairments while trying to maximize feasible free wavelengths for future requests, and minimize the effect on existing lightpaths. The weight-assignment process can be made off-line, using the idle time between requests. Through the simulation studies, our approaches show good performance in terms bandwidth blocking ratio, utilization, and resource consumption with respect to the existing approaches.

The rest of the study is organized as follows: In Section 2, we review previous works on MLR network problems. In Section 3, the bit-error-rate (BER) estimation model used in our study is discussed. A formal definition of the dynamic lightpath provisioning problem in MLR networks and the proposed algorithms are given in Section 4. Section 5 provides performance evaluation of proposed algorithms. Finally, Section 6 concludes the study.

2. Related works

Various studies have been reported on the design of MLR networks considering static traffic. The authors in [7] deal with the design of MLR networks. A novel node architecture, where transparent *Etherpaths* (i.e., Ethernet tunnels on lightpaths) are established between these nodes, is proposed. The work in [8] shows that MLR networks are more cost-effective than SLR networks. In [9], the authors aim to reduce the network cost in MLR networks using multiple modulation formats. In [10], the authors study protection in MLR networks, and present cost effective transparent virtual topology design schemes. In [11], the authors investigate the planning of 10/40 Gbps MLR networks, considering nonlinear interferences between 10 and 40 Gbps channels. In [12], the authors present RWA algorithms that adapt the transmission reach of each connection according to the use of the modulation formats/line rates in the network. The algorithms allow to plan the network so as to alleviate cross-rate interference effects. In [13], design algorithms for MLR translucent networks considering energy efficiency is proposed. In [14], design and planning of translucent MLR networks is investigated, considering multiple modulation formats with different reaches.

While various studies exist on the design of MLR networks with static traffic, there are only a few studies on impairment-aware dynamic lightpath provisioning problem in MLR networks. The authors in [15] consider the dynamic RWA problem in MLR networks without considering the impairments. The impairments are handled in [16] with the assumption of dynamic launch power capability, and a launch power control algorithm is proposed to improve the performance in terms of blocking probability. A path computation element (PCE) algorithm is proposed in [17] and an architecture to implement impairment-aware lightpath provisioning is defined [18]. In [19,20], the authors investigate impairment-aware

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

lightpath provisioning in MLR networks based on PCE. They propose various schemes based on *worst-case* and *guard-band*. In the worst-case scenario, a phase modulated (DQPSK and DP-QPSK) lightpath has OOK lightpaths on both neighboring wavelengths. In [21], the authors investigate different PCE architectures and experimentally evaluate PCE architectural solutions. Different solutions employ either combined or separated impairment-estimation and RWA, with on-line and off-line computation of impairment-validated paths. In [22], a scheme for dynamic grooming and RWA in translucent MLR networks is proposed. In [23], the authors propose various dynamic lightpath provisioning algorithms based on inverse multiplexing, which is a technique that transmits the signals with low line rates where high line rates are not feasible due to PLIs. In [24], the authors try to improve the dynamic lightpath provisioning performance by setting the appropriate launch power for each connection.

This study is one of the few dealing with the dynamic impairment-aware lightpath provisioning problem in MLR networks. We do not consider traffic grooming in this study. We propose two practical and well-performing approaches, which can be easily implemented. The weighted approach (W-RWA) proposed in this study captures the instantaneous state of the network and tracks the PLIs on each channel with a weight-assignment scheme. The algorithm selects the wavelengths which are less exposed to impairments, thus impairment calculation and RWA are handled jointly. The algorithm also tries to leave feasible wavelengths for future requests, and avoids to affect the existing lightpaths. W-RWA can make use of the idle time in between the connection requests to assign revised weights so as to reduce the computation time during lightpath establishment.

In this study, we also propose a simple scheme (FWIA) to deal with XPM effects of adjacent OOK modulated signals, based on wavelength-interval reservation for different line rates. A lightpath with a specific line rate is established over a wavelength in the related interval. This approach decreases the computation time, and it is easy to implement.

3. BER estimation

The signal quality degrades due to physical-layer impairments along the optical tranparent path. Therefore, the signal quality at the receiver side should be evaluated. 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].

A major impairment is the linear noise accumulated along the path induced by in-line optical amplifiers and non-ideal isolation of switch components. Optical signal-to-noise ratio (OSNR) is the ratio between the total signal power and the noise power on the reference bandwidth [25]:

$$OSNR = \frac{P_{out}(\lambda)}{N_{out}(\lambda)} \tag{1}$$

where the output power of the signal (P_{out}) denotes the signal power at the receiver, and the noise power (N_{out}) denotes the undesired signal power accumulated along the path on a given wavelength (λ).

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 [26]. XPM and SPM are taken into account using the approximation given in [20].

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

3.1. On-Off Keying (OOK) Systems

BER of a signal depends on *Q*-factor as [27]:

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

With Gaussian distribution of the intensity of impair-ments, the *Q* parameter is given as [20]:

$$Q = \frac{2\rho}{\sqrt{M} + \sqrt{M+4\rho}} \tag{3}$$

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 $\rho = nB_{ref}T \cdot OSNR$, 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 1

3.2. Quadrature phase shift keying (QPSK) systems

Different from OOK channels, signal quality of QPSK channels are 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 n se differs from a given angle (θ) approximately by $Q(\sqrt{\frac{oi}{2\rho}}\ \sin\theta)$. Using this information, we can use the BER evaluation model given in Eq. (2), with the following formula for *Q*-factor [20]:

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

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

The variance of non-linear phase noise has two components: SPM and XPM variances ($\sigma_{NL}^2 = \sigma_{SPM}^2 + \sigma_{XPM}^2$). These noise variances are approximated differently for DQPSK and DP-QPSK systems. For DQPSK, SPM contribution of phase noise variance is calculated according to: $\sigma_{SPM}^2 \approx 4\phi_{SPM}^2/(3\rho)$, while in *DP-QPSK*, variance of SPM noise is approximated as: $\sigma_{SPM}^2 \approx 2\phi_{SPM}^2/(3\rho)$. ϕ_{SPM} is the optical phase shift due to SPM effect. Variance of XPM, σ^2_{XPM}, is calculated according to the model given in [20].

4. Problem definition and proposed algorithms

In this study, we consider the dynamic lightpath provisioning problem for in MLR optical WDM networks, subject to physical-layer impairments. This problem is a cross-layer optimization problem which aims to maximize the established connections at the network layer, while assuring signal quality at the physical layer. The problem can be formally stated as follows:

The inputs of the problem are:

- A dynamic connection request with a given rate,
- Physical topology,
- Number of wavelengths carried by each fiber,
- Current network state, and
- PLI parameters.

The goal is to determine:

- Route over which the lightpath should be set up and
- Wavelength to be assigned.

The objective of the problem is to maximize the number of established connections while satisfying the given BER for incoming connection, and to avoid disrupting the existing lightpaths. The problem is NP-hard, since it contains the NP-hard RWA problem [28] as a special case.

We propose two approaches to handle PLIs for dynamic lightpath provisioning in MLR networks. The proposed approaches are as follows.

4.1. Fixed wavelength-interval allocation (FWIA)

Linear and nonlinear noise accumulated along the path degrades the optical signal quality. This noise depends on various system parameters (e.g., symbol rate, number of channels, channel spacing, and fiber type). Interchannel nonlinearities are particularly important to advanced modulation formats at high (40G/100G) bit rates. Although every optical channel induces interchannel nonlinearity on neighboring channels, adjacency of OOK channels has more detrimental effects on 40G/100G channels. The work in [29] shows that 10G OOK and 40G DPSK channels have different impacts on 100G DP-QPSK channels. To prevent, especially, OOK channels to negatively affect high (40G/100G) bit-rate channels, FWIA approach partitions wavelengths into groups, where each group is assigned to a different modulation format. This kind of wavelength allocation considers PLIs implicitly, and avoids assigning adjacent channels to different modulation formats.

The number of wavelength groups is equal to the number of different line rates (see Fig. 1). The number of wavelengths to be allocated for each line rate can be determined by the network operator according to statistical data on distribution of line rates of the requests.

The proposed FWIA scheme for routing and wavelength assignment is given in Algorithm 1.

Algorithm 1. Fixed Wavelength-Interval Allocation (FWIA).

```
I–   Get the request.
II–  Find shortest path from s to d with an available wavelength,
       • If a path with an available wavelength does not exist, reject the request.
       • Else find an appropriate wavelength:
           — Start from the center of the allocated wavelength-interval.
           — Search towards the sides of the interval.
III– Validate the path for minimum BER requirements (candidate).
IV–  Verify existing lightpaths:
       • If any of the existing lightpaths' BER becomes unacceptable,
           — Look for another wavelength (Multiple Attempt).
           — Reject the request (Single Attempt).
V–   Set up the lightpath.
VI–  Tear down the lightpath after its holding time.
```

Before any connection request comes, total wavelengths are partitioned into intervals. Each wavelength-interval is allocated to a single line rate. When a connection request comes, the algorithm first finds the shortest path, and then looks for an appropriate wavelength. For an incoming request, from source (s) to destination (d), a wavelength is selected from the group allocated for the requested line rate. Search for an appropriate wavelength starts from the center wavelength of the allocated group of wavelengths to find the one that is less exposed to XPM, and to leave more number of feasible wavelengths for future requests. The search proceeds towards the sides. First, one half of the interval which does not cause (or expose) to XPM effect is searched. If there is not an available wavelength in this half of the interval, the algorithm searches the other half of the interval, again beginning from the center. After finding an available wavelength, BER is estimated for this path and wavelength, considering the current state of the network. If the estimated BER value is acceptable, then this (path, wavelength) pair is called the candidate lightpath. Then,

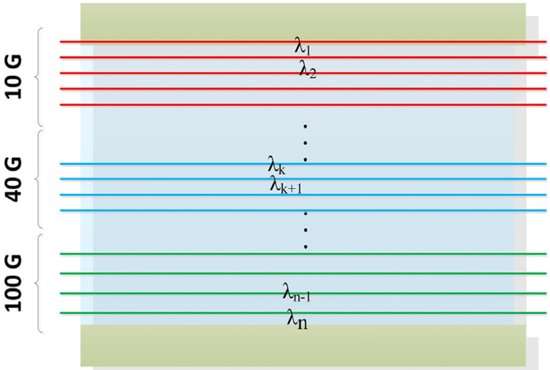

Fig. 1. Fixed Wavelength-Interval Allocation (FWIA).

the existing lightpaths are examined. If any of the existing lightpaths is damaged by this candidate lightpath, the algorithm searches for another wavelength. This is called *multiple attempt* scenario. In *single attempt* scenario, if the candidate lightpath damages any existing lightpath, the request is rejected without looking for another wavelength.

4.2. Weighted routing and wavelength assignment (W-RWA)

In this approach, we employ an auxiliary graph $G(V,E)$, by replicating the network's original graph $G_0(V_0,E_0)$ for each line rate. The auxiliary graph is used to assign weight values to the wavelengths to account for the impairments in MLR networks.

4.2.1. Auxiliary graph construction

To construct the auxiliary graph $G(V,E)$, we first replicate the physical nodes (V_0). The ith vertex of the auxiliary graph (Fig. 2-a) 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. 2-b) 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 ($W^{\lambda}_{i,j,k}$), which is assigned according to the current state of the network (Fig. 2-c). 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, CD, and PMD). After each lightpath is established or released, the weight values ($W^{\lambda}_{s-d,k}$) are recalculated along the path ($s-d$) for the wavelengths within the *guard band* of the newly established lightpath. Guard band (GB) is the number of wavelengths between two lightpaths, beyond which the effect of a lightpath on the other can be neglected. The GB value is evaluated as in [20]. The weight values are calculated as discussed below.

4.2.2. Weight assignment

We use a weight-assignment scheme to capture the PLIs [30,24]. The weight values represent linear and non-linear impairments that occur on the physical links (ASE, losses, CD, 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 of 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 crosstalk (inter and intra-band crosstalk [31]) are considered in this study.

Each vertex j of the auxiliary graph is assigned a weight value ($W^{\lambda}_{V^j_k}$) 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 ($W^{\lambda}_{V^j_k}$) as follows:

$$W^{\lambda}_{V^j_k} = \omega^{\lambda}_{XT_a} \cdot \nu^{\lambda\mp 1}_{XT_a} + \sum_{n=1}^{N} \omega^{\lambda}_{XT_b} \cdot \nu^{\lambda,n}_{XT_b} + \kappa \tag{5}$$

where $\omega^{\lambda}_{XT_a}$ and $\omega^{\lambda}_{XT_b}$ indicate the predefined weight factors of the crosstalk components; $\nu^{\lambda\mp 1}_{XT_a}$ and $\nu^{\lambda,n}_{XT_b}$ are the binary variables indicating the presence of a lightpath causing crosstalk on port n 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 $W^{\lambda}_{i,j,k}$. The initial weight values are calculated considering ASE, CD, and SPM using Eq. (6). The weight value of the affected wavelengths of the links along the path are re-calculated 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. (5). The wavelengths (λ_d) within guard band ($\mp GB$) 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 $1/(\Delta\lambda)^2$ [20], 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 ($E_k^{i,j}$) as follows:

$$W^{\lambda_d}_{i,j,k} = W^{\lambda_d}_{V^j_k} + m.\omega^{\lambda}_{ASE} + \omega^{\lambda}_{CD} + \omega^{\lambda}_{SPM} + \sum_{k=1}^{R} \sum_{g=\lambda_n-GB}^{\lambda_n+GB} \frac{1}{(\Delta\lambda)^2} \omega_{XPM} \cdot \nu_g^{i,j,k} + \zeta \tag{6}$$

where m is the number of spans within the link, R is the number of line rates, ω^{λ}_{ASE}, ω^{λ}_{CD}, ω^{λ}_{SPM} , and ω^{k}_{XPM} are the predefined weight factors of ASE, CD, 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. $\nu_g^{i,j,k}$ denotes the existence of affecting lightpaths with rate k on wavelength g, and ζ stands for the adjusting weight value for other impairments. Together with κ value in Eq. (5), ζ is used to help the algorithm to select the lower hop-count path when more than one path have same total weight value. The para-meters used in link-weight evaluation are given in Table 1. *Same modulation promotion*: Another feature of the weight-assignment scheme is the *same modulation promo-tion*, which gives promotion points (Ξ) to adjacent chan-nels that use the same line rate (k) as the already established lightpaths. After each lightpath is established, a *promotion* value is subtracted from the weight of the wavelengths (λ_d) within GB, according to their distances ($|\lambda_n - \lambda_d|$) to the established lightpath over λ_n. This promo-tion value is relatively small compared to the weight values of impairments. The weight value of a wavelength (λ_d) at a specific bit rate k on a link (i,j) is promoted as

$$W^{\lambda_d}_{i,j,k} = W^{\lambda_d}_{i,j,k} + (-1)e^{(-1)|\lambda_n - \lambda_d|} \cdot \Xi \tag{7}$$

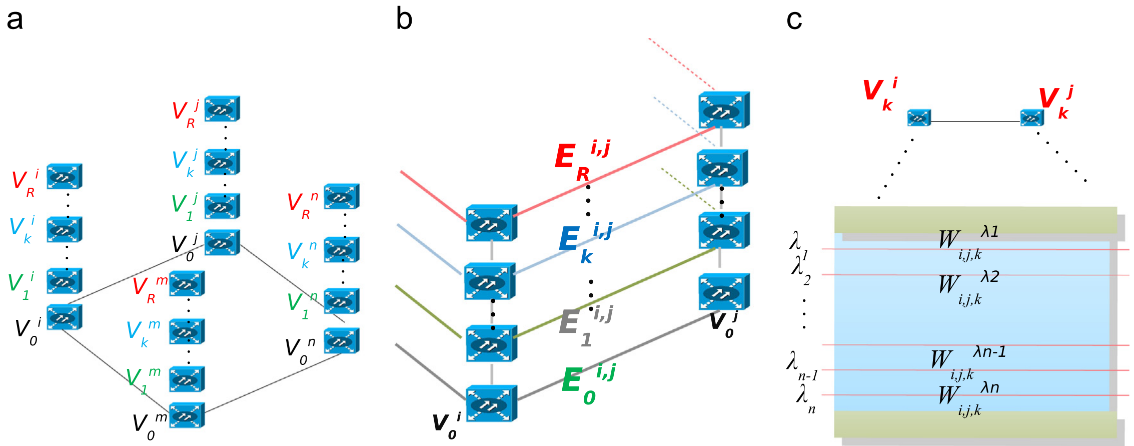

Fig. 2. Auxiliary graph construction. (a) Physical nodes are replicated. (b) Physical links are replicated. (c) Each wavelength on a link associated with a weight value.

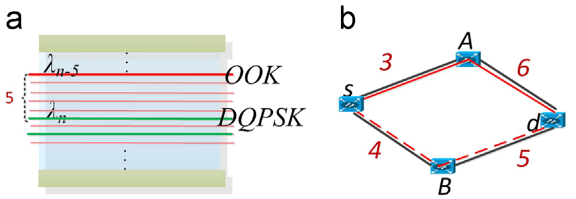

Fig. 3. Maximum spectral distance calculation.

With this promotion, the same modulation format is encouraged to be selected for adjacent channels, so the lightpaths using the same modulation format tend to be closely located.

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

4.2.3. *Algorithm*

The W-RWA is given in Algorithm 2.

Algorithm 2. Impairment-Aware Weighted-RWA (W-RWA).

```
I– Initialize the Auxiliary Graph.
II– Get the request.
III– Find minimum weighted path(s).
    • If no available path exists:
        – Reject the request.
      If more than one path available with same weight value:
    •   – Choose the path with minimum estimated BER.
            ∗ If more than one have same estimated BER.
    • Validate the path for minimum BER requirements.
    • Verify existing lightpaths.
        – If any existing lightpath's BER becomes unacceptable:
            ∗ Look for another minimum-weighted path (Multiple Attempt)
IV– Set up the lightpath.
V– Update the Auxiliary Graph.
    • Add weight to adjacent wavelengths for other modulation formats, $W_{i,j,R}^{\lambda}$.
    • Add promotion points ($\Xi$) to neighboring wavelengths for the same modulation format.
VI– Release the lightpath after holding time.
V– Update (Inverse) the Auxiliary Graph.
```

When a request arrives, the algorithm looks for the minimum-weighted path over the auxiliary graph. The algorithm guarantees the signal quality along the lightpath by avoiding higher-weight paths. If a path cannot be found, then the request is rejected (resource blocking). It is also possible to find more than one path with the same minimum total-weight value. In this case, estimated BER values of these paths are evaluated, and the path with minimum BER is selected.

For low traffic loads, we may obtain same estimated BER values for different wavelengths on the same route. In this case, the wavelength that has the largest *maximum spectral distance* (MSD) is selected. Maximum spectral distance is the distance of DQPSK and DP-QPSK channels to the closest OOK channels on the same link.

In Fig. 3-a, spectral distance of the projected link is 5, where λ_n and $\lambda_{n\text{-}5}$ are occupied with different line rates. The minimum of these values along the path gives the maximum spectral distance of the path. Given the paths in Fig. 3-b (the numbers are the spectral distances of links), the path between *s* and *d* passing over node *A* (solid line) has minimum distance of 3, while the path passing over node *B* (dashed line) has minimum distance of 4 along the path. In case of having same total weight value of these paths, the path with minimum distance of 4 is selected.

After finding the appropriate path and wavelength, the quality of signal is validated using the BER evaluation model (see Section 3). If the path and wavelength found is infeasible because of the PLIs, the request is rejected (physical-layer blocking). The selected path and the wavelength is called a *candidate*, if the estimated BER value is acceptable. Before establishing the lightpath over this candidate path and wavelength, the signal quality of existing lightpaths (only the ones which are expected to be affected from the new lightpath) are also verified.

Promotion points are added to neighboring wavelengths for the same modulation formats. With the help of *same modulation promotion*, the algorithm improves the awareness of the current state of the network, minimizes the effects of XPM, and avoids degrading the signal quality of already established lightpaths.

Let V be the number of vertices, and E be the number of edges, then the worst-case complexity of the W-RWA algorithm is $O(w \times (|V|\log V + |E|) + O_{BER})$, where O_{BER} is the computational cost of BER calculation. Since all the wavelengths are associated with a weight value, the W-RWA algorithm runs the shortest-path algorithm w times. The FWIA approach looks for the shortest path that has an available wavelength within the allocated wavelength interval. Thus, it runs the shortest-path algorithm w/k times for worst case, where k is the number of line rates.

5. Performance ealuation

In this study, we consider an optical WDM network in which each node can support transmission at 10, 40, and 100 Gbps. NSFNET topology, with 14 node and 21 links, is used to evaluate the performance of different schemes. Fiber links are assumed to have inline (EDFA) amplifiers every 82 km, with 70 km standard single mode fiber and 12 km dispersion compensation fiber. We consider a fixed grid with 50 GHz spacing carrying 80 wavelengths. Wavelength-continuity constraint is applied at intermediate nodes. Connection requests arrive according to Poisson distribution with exponentially-distributed holding time. Requests for different line rates are dynamically generated according to two distributions: uniform and skewed. For uniform distribution, the bandwidth of the request is uniformly chosen among 10, 40, and 100 Gbps. The skewed traffic profile generates equal amount of bandwidth request for each line rate, using 0.075, 0.185, 0.740 probabilities for 100G, 40G, and 10G, respectively. In FWIA, wavelengths are equally partitioned into groups as the number of line rates. We run the simulations for one million connection requests. Other system parameters are given in Table 1.

Table 1
System parameters.

Parameters	**Value**
Number of wavelengths, W	80
Line rates (Gbps)	10, 40, 100
BER threshold	10^{-4}
Signal launch power (mW)	1
B_{ref} (GHz)	12.5
Gain of EDFA (G_{in}, G_{out})(dB)	20.8, 19
Amplifier noise factor (F)(dB)	4
Fiber loss factor, $\alpha_{SMF}, \alpha_{DCF}$ (dB/km)	0.2, 0.6
Dispersion, D_{SMF}, D_{DCF} ps/(km nm)	17, 92
PMD coefficient, D_{PMD} ps/$\sqrt{\text{km}}$	0.2
$L_{SW}, L_{DMX}, L_{MX}, L_{tap}$ (dB)	5, 5.5, 4.5, 1
X_{SW}, X_{DMX}, X_{MX} (dB)	-45, -25, -25
Symbol time (10,40,100) (ps)	100, 50, 40
Kerr coefficient, n_2 (m^2/W)	3
$A_{eff}SMF$, $A_{eff}DCF$ (μm^2)	80, 30
Filtering effect (K_{DQPSK}, K_{QPSK})	1, 7
$\omega^{\lambda}_{XT_a}$, $\omega^{\lambda}_{\underset{r}{XT_b}}$	0.05, 0.025
ω^{λ}_{SPM}, ω_{XPM}	0.1, 0.5
ω^{λ}_{CD}, ω^{λ}_{ASE}	0.4, 1
κ, ζ, Ξ	0.01, 0.5, 0.0005

The quality of the signal is evaluated using the BER model given in Section 3. It is shown in [3] that, 40G channels do not have so much XPM effect on 100G channels. In our examples, we assume that phase-modulated (40/100G) channels do not to have XPM effect on each other, while the predefined ASE, CD, and SPM weights are assumed to be the same for all wavelengths.

We compared our proposed approaches (W-RWA and FWIA) with the *First-Fit with Worst-case scenario with GB* (FF-W-GB) approach, given in [20]. In FF-W-GB, first XPM is considered in worst-case scenario. If the estimated BER of the lightpath is acceptable in worst case, GB is not considered to establish the lightpath. If the BER is acceptable only by neglecting XPM, neighboring wavelengths are reserved to be GB.

We also compared our approaches with the *Shortest-Path with Best-BER* (SP-BB) algorithm. SP-BB is a modified version of the Best-BER (BB) algorithm introduced in [32], which combines the procedures of wavelength assignment and BER estimation. In SP-BB, first the shortest path is found, and then, BER value is estimated for each wavelength on the shortest path, and finally the Best-BER (the one having the minimum BER value) channel is selected. The shortest-path algorithm is modified to find the shortest path with at least one available wavelength. This modification is made to have a fair comparison with the Weighted-RWA approach. W-RWA selects the minimum-weight path, which is not necessarily the shortest path. If the estimated BER value is within the acceptable thresh-old, then the path and wavelength found is regarded as a candidate; otherwise, the request is rejected. After finding the candidate path and wavelength, existing lightpaths, which are expected to be affected by the candidate light-path, are checked for signal quality.

Calculation of pure blocking probability treats all requests as the same, but blocking a request with 100G causes 10 times more throughput loss than a 10G request. Thus, blocking different requests with different line rates is not the same in terms of the achieved throughput. Bandwidth blocking ratio (BBR) is defined as the amount of bandwidth blocked over the amount of bandwidth offered [33].

Fig. 4 shows the BBR for different lightpath provisioning schemes with uniformly distributed traffic. In multiple-attempt scenario, FF-W-GB algorithm shows better performance than the other approaches for low link utilization levels. It exploits the benefit of putting guard band for higher line rates, but its performance degrades due to high wavelength utilization for high traffic loads. For low and medium traffic loads, SP-BB approach has slightly worse performance than W-RWA. For high utilization levels, W-RWA shows better performance, because W-RWA is rate aware and it aims at keeping more number of feasible wavelengths for future requests. To use multiple attempts, W-RWA picks the wavelengths having 1% weight more than the total weight of the minimum-weighted path. FWIA shows fair performance for the multiple-attempt scenario.

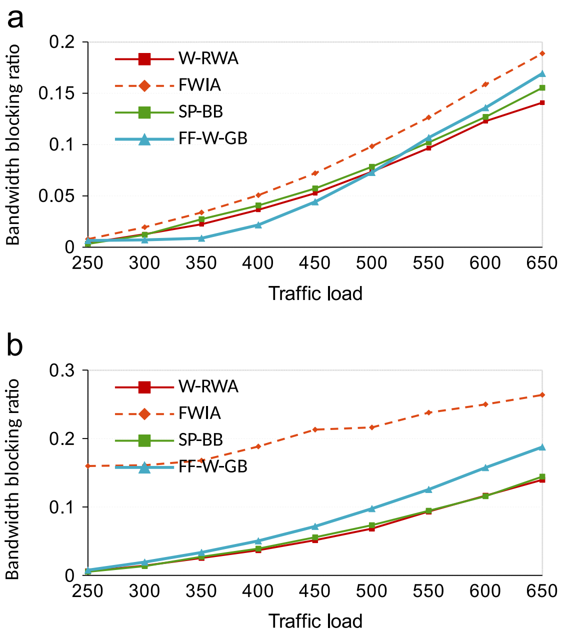

Fig. 4. Bandwidth blocking ratio of different schemes with (a) multiple-attempt and (b) single-attempt scenarios, for uniformly distributed traffic.

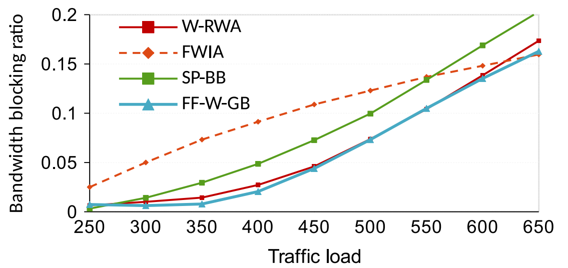

Fig. 5. Bandwidth blocking ratio of different schemes with multiple-attempt scenario, for skewed traffic.

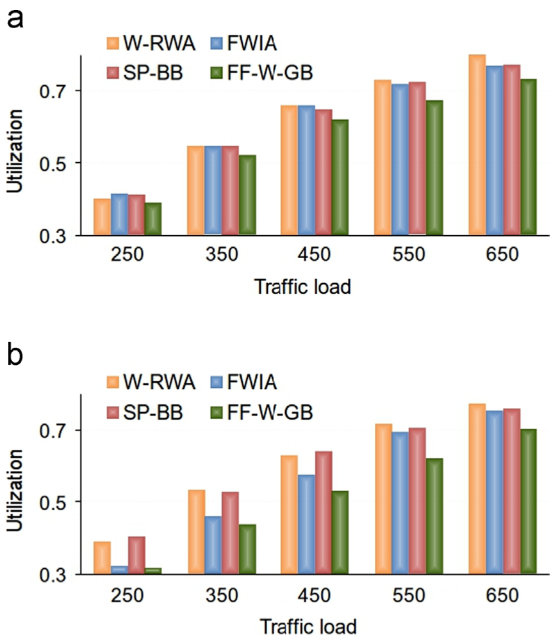

Fig. 6. Network utilization with different schemes. (a) Multiple attempt and (b) Single attempt.

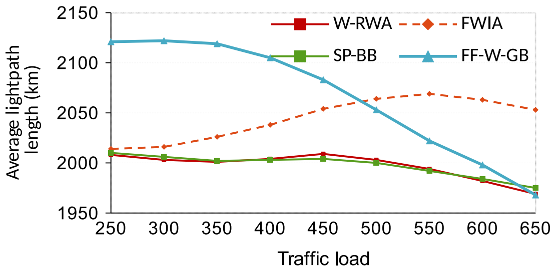

Fig. 7. Average length of established lightpaths.

In the single-attempt scenario the difference between performances of SP-BB and W-RWA is not significant. These algorithms, W-RWA and SP-BB, show lower blocking than FF-W-GB and FWIA. The FWIA algorithm does not search for the wavelength having the minimum BER. It selects the first available wavelength, thus, it suffers from XT effect of same modulation channels. These results show that, in the multiple-attempt scenario, W-RWA takes the advantage of considering different physical paths having the same weight value.

We ran the simulations also for a skewed traffic profile. Bandwidth blocking ratio for skewed traffic with multiple-attempt scenario is given in Fig. 5. Line-rate-aware approaches, W-RWA and FF-W-GB, give better BBR than the others for low and medium traffic loads. In skewed traffic profile, total bandwidth offered to the network is equal for each line rate, so the number of lightpaths with low line rate is higher than with high line rate. Therefore, more wavelength channels are occupied with low-line-rate channels, and this causes more impairment on the network. Since FWIA allocates wavelengths for each line rate, the algorithm succeeds in establishing high-line-rate lightpaths over allocated wavelengths, even for high traffic loads. Thus, FWIA shows better performance than the other algorithms for very high traffic loads.

Fig. 6 indicates the maximum utilization levels of the network with different algorithms for different traffic loads. The network reaches the highest utilization level using W-RWA algorithm for all traffic loads. While, the utilization levels reached by SP-BB are slightly lower than the levels achieved by W-RWA, the levels achieved by FWIA are significantly lower than W-RWA, especially for low traffic loads in single attempt scenario. This result indicates that the algorithm suffers from XT effect of adjacent channels. Since FF-W-GB approach puts GB to avoid XPM effect of low line rates, this algorithm reaches lower utilization levels than the others.

Although W-RWA exploits the advantage of considering different paths, it does not require significantly longer paths than shortest-path-based approaches. Results for average lightpath length are shown in Fig. 7. The general tendency of average-length decrease for higher loads occurs because of decreasing performance. The algorithms

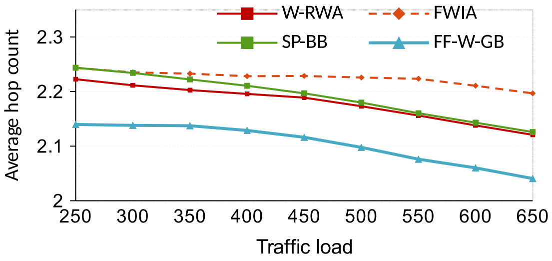

Fig. 8. Average hop count of established lightpaths.

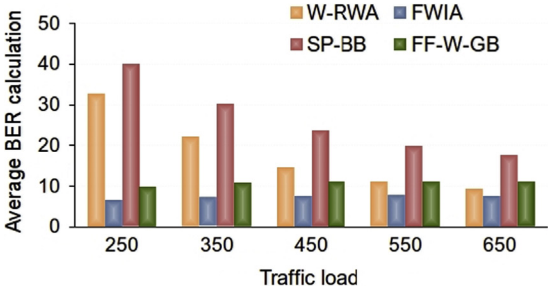

Fig. 9. Average BER calculation per connection request.

fail to establish lightpaths with longer paths for higher loads. W-RWA and SP-BB have similar average lightpath lengths. Shortest-path-based approaches (FWIA and SP-BB) have different average lightpath lengths because the shortest-path algorithm is modified to find the shortest path that has at least one available wavelength. The difference comes from lightpath establishment performances of algorithms. FWIA approach is more susceptible to network load in terms of average lightpath length. Since the lightpath provisioning performance of the algorithm is lower than W-RWA and SP-BB algorithms, it manages to find available wavelengths to establish lightpaths for medium traffic while W-RWA and SP-BB cannot. The FF-W-GB approach uses hop count to find the appropriate path, thus the average length of established lightpaths is larger than the others for low and medium traffic loads. For high traffic loads, the algorithms hardly find available wavelengths, thus, the average length of established lightpaths converge at high traffic loads.

We also evaluated the average hop count of established lightpaths (Fig. 8). Each hop means an assigned wavelength on a link. Thus, this metric gives an idea about the performance of the algorithms in terms of network resource consumption. Since FF-W-GB uses hop count to find shortest paths, this algorithm shows better performance than the others. The W-RWA algorithm shows slightly better performance than SP-BB for low loads and similar performance for high traffic loads. W-RWA takes advantage of evaluating more than one path from source to destination, where those paths may have less total weight than the shortest path. Although FWIA gives close performance with SP-BB for low traffic loads, it is more susceptible to traffic load. When we consider Figs. 4 and 8 together, we observe that SP-BB approach uses more network resources than W-RWA in terms of wavelength-links to decrease the bandwidth blocking ratio.

Fig. 10. Time spent per connection request.

All the algorithms use the same BER estimation model. The algorithms make BER calculations to check both the candidate lightpath and the existing lightpaths. W-RWA makes additional BER calculation only when more than one path may have the same total weight value. Let *w* be the number of wavelengths, then W-RWA makes *w* times BER calculation for the worst case. This happens at the beginning, when the network is empty. SP-BB algorithm also makes *w* times additional BER calculations for the worst case. In average cases, SP-BB makes BER calculations for all available wavelengths on the selected path, where W-RWA makes only for minimum weighted wavelengths. These extra calculations bring computational burden to the algorithms. Fig. 9 shows the average number of BER calculations per connection request. FWIA does not search the best-BER-valued wavelength, thus it computes much less BER calculations per connection request than the others. Since there are more available wavelengths for lower traffic loads, the algorithms make more BER calculation at the beginning.

In developing dynamic environments, computation time of the algorithms have special importance. Fig. 10 shows the average time that is spent for one connection request by algorithms in the same simulation environment. The results show that FWIA approach takes less time than the others. Considering the blocking and the computational time performance together, we can say that FWIA is a practical approach especially for low traffic loads.

We also evaluated the W-RWA approach with and without same modulation promotion (Section 4.2.2). This amendment to the proposed algorithm brings up to 0.8% improvement in blocking performance, which might be considered as minor.

6. Conclusion

In this study, we investigated the impairment-aware lightpath provisioning problem in MLR networks. In our MLR model, the nodes are capable to operate at 10, 40, and 100 Gbps, which require OOK, DQPSK, and DP-QPSK modulations, respectively. We proposed two different approaches (W-RWA and FWIA) for the problem. FWIA partitions all wavelengths into groups, and assigns each group of wavelength to a different line rate. W-RWA is based on an auxiliary graph which is constructed and updated according to the physical-layer impairments and the current state of the network.

Our algorithms are evaluated through simulations and compared with other methods. Our results indicate that

W-RWA outperforms the others in terms of BBR and pure blocking performance. Network utilization reaches maximum level using W-RWA. We also evaluated the average length of lightpaths, and observed that W-RWA selects slightly longer lightpaths to assure better signal quality. Resource usage of W-RWA is similar to shortest-path-based approaches in terms of hop count. Overall, the performance of W-RWA and its success in making a part of the calculations off-line for on-line provisioning makes it superior to the compared algorithms. The FWIA algorithm seems to be a practical approach to consider PLIs implicitly. It shows good performance especially for lightly loaded networks, and its computational burden is considerably lower than the others.

The weight factors and the other parameters can be further studied to find the optimum combination for different topologies.

Acknowledgments

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