Connection Provisioning With Transmission Impairment Consideration in Optical WDM Networks With High-Speed Channels

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***Abstract*—We investigate new connection-provisioning algorithms to efficiently provide signal-quality-guaranteed connections in an optical wavelength-division-multiplexing (WDM) mesh network operating with high-speed wavelength channels. In an optical network, a connection is set up to carry a data signal via an all-optical channel (lightpath) from its source to destination node. The optical signal transmitted along the lightpath may need to travel through a number of crossconnect switches (OXCs), optical amplifiers, and fiber segments. While the signal propagates toward its destination, the optical components would continuously degrade the signal quality by inducing impairments. When the signal degradation is so severe that the received bit-error rate (BER) becomes unacceptably high, the lightpath would not be able to provide good service quality to a connection request. Such a lightpath, which has poor signal quality due to transmission impairments in the physical layer, should not be used for connection provisioning in the network layer. With increasing channel bit rate to 10 Gb/s or higher, fiber linear and nonlinear impairments become prominent factors, which affect the signal quality. Thus, new techniques in both physical layer and network layer are necessary for mitigating impairments to accommodate high-speed traffic. Therefore, to ensure service quality of high-speed connections, we develop intelligent *impairment-aware* routing and wavelength assignment (RWA) algorithms, which automatically consider the effects of high-speed transmission impairment when setting up a lightpath. The main contribution of our paper is that we investigate a novel hierarchical RWA model for high-speed connection provisioning where the optical signal-to-noise ratio (OSNR) and polarization mode dispersion (PMD) effect are estimated in the physical layer, and regarded as metrics for lightpath computation in the network layer. The performance of the proposed connection-provisioning strategies is demonstrated to be promising through illustrative numerical examples.**

***Index Terms*—Connection provisioning, impairment-aware RWA, optical signal-to-noise ratio (OSNR), optical WDM network, polarization mode dispersion (PMD), signal quality, transmission impairment.**

I. Introduction

A transparent optical WDM network is a promising candidate for the next-generation backbone network. In a *transparent* network, an optical signal travels through the network while remaining in the optical domain from source node to destination node without any optical-electrical-optical (OEO) conversion at intermediate nodes, thus eliminating the electronic bottleneck in current networks. However, in an *opaque* network, OEO conversion is employed at every node to regenerate and retransmit the data signal. The expenses associated with such opaque transmission are quite high, mainly due to the large number of regenerators required at each node of a national-scale network. The cost could be reduced in a *translucent network* where the regeneration functionality is only employed at some nodes instead of at all nodes. The eventual goal of reduction of OEO conversion and electronic switches leads to the concept of the all-optical transparent network [1]–[3]. It has been shown that the economy and scalability of the network are greatly enhanced through the use of a transparent networking layer [1]. Hence, we focus our attention on such a transparent network wherein a connection is set up to carry data traffic via an all-optical WDM channel, called a *lightpath*. Setting up a lightpath for a connection request by using a routing and wavelength assignment (RWA) technique [4] is known as connection provisioning. Intelligent connection provisioning is an important traffic-engineering problem for minimizing cost and for better utilizing network resources.

Many connection-provisioning problems have been investigated under the assumption that the optical medium is an ideal one which can carry data signals without any bit error. Under this circumstance, the effects of transmission impairments on the signal quality of a connection do not need to be considered. Nevertheless, transmission impairments, which occur in fibers and optical components, may significantly affect the quality of a lightpath [2], [5]–[8]. Hence, we need to consider the impact of impairments during connection provisioning.

Because of transparency of an all-optical network, the elimination of OEO conversion leads to the loss of a potential benefit that signal degradations will be cleaned up when the signal is regenerated at intermediate nodes. Since a transmitted data signal remains in the optical domain for the entire lightpath, noise and signal distortions due to impairment effects accumulate while the signal travels through the lightpath, and they may cause significant signal degradation. At the destination node, the received signal quality may be so poor that the bit-error rate (BER) can reach an unacceptably high value, and thus the lightpath is not usable [5]–[7]. In an optical network, since lightpaths are setup through a variable number of independent fiber links, which may have different physical characteristics,

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the end-to-end transmission impairments will vary with each lightpath. Moreover, the impairments on a lightpath also may change with network state (i.e., traffic distribution) because of the interchannel crosstalk. Hence, setting up a new lightpath may slightly increase the received BER of existing lightpaths, while tearing down an existing lightpath may slightly decrease the received BER of remaining lightpaths. Without physical-impairment awareness, a network-layer RWA algorithm might provision a lightpath which cannot meet the signal-quality requirement. Therefore, the control plane of an optical transparent network should incorporate the characteristics of the physical layer in setting up a lightpath for a new connection. To greatly simplify the network management, some margin in BER requirement could be considered to mitigate the effects of traffic distribution on a lightpath's quality due to the BER fluctuation.

The transmission impairments induced by nonideal physical-layer components can be classified into two categories: linear and nonlinear. Some important linear impairments are amplifier noise, polarization mode dispersion (PMD), group velocity dispersion (GVD), component crosstalk, etc.; and some important nonlinear impairments are four-wave mixing (FWM), self-phase modulation (SPM), cross-phase modulation (XPM), scattering, etc. The linear impairments are independent of signal power. Their effects on end-to-end lightpath might be estimated from link parameters, and hence could be handled as a constraint on routing [8]. The nonlinear effects are significantly more complex. Moreover, a general analytical model for some impairments due to fiber nonlinearity is not readily available at the moment [9]–[11].

Our goal in this paper is to assess how network performance could be affected by transmission impairments, and to design intelligent connection-provisioning algorithms which improve network performance by considering the impacts of impairments in the routing procedure. Thus, instead of considering all impairments in a transmission system, our study is based on the assumption that (a) the dominant impairments of a transmission system are noise of Raman amplifier, PMD, and crosstalk at optical crossconnects (OXCs) which are significant linear impairments in high-speed ($\geq$ 10 Gb/s) networks [8], [12]; and (b) GVD can be adequately compensated on a per-link basis. Thus, we propose two novel impairment-aware RWAs, called *impairment-aware best-path (IABP) algorithm* and *impairment-aware first-fit (IAFF) algorithm*, for a per-channel bit rate of 10 Gb/s (or higher) in a typical nationwide mesh network.

In our approaches, we incorporate the impact of the physical layer in network-layer connection provisioning through a new hierarchical RWA model. The model for lightpath assignment consists of two steps: lightpath computation in a network-layer module and lightpath verification in a physical-layer module. In the physical-layer module, we model the impairment effects and keep track of them as the signal travels through a lightpath. The signal quality is analytically estimated at the lightpath's destination, and provided as feedback to the network-layer module. After getting the lightpath's quality information from the physical layer, the network connection admission is controlled according to not only the free-resources status but also the signal-quality requirement. Hence, our impairment-aware RWA algorithms automatically provision a signal-quality-guaranteed lightpath for a connection request.

Currently, how to incorporate physical-layer impairments in network-design problems is attracting more attention from researchers. Studies have been devoted to optical transparent networks. Two foci are: effects of impairments on network performance [5]–[7], and network design with impairment consideration [13]–[15]. References [6] and [7] show that the network performance (i.e., the network's call-blocking performance or device savings) can be significantly affected by transmission impairments in low-speed (typically 1 Gb/s per channel) mesh networks where linear impairments, such as noise of erbium-doped fiber amplifier (EDFA) and switch crosstalk could be the dominant effects. Reference [5] investigated GVD and SPM effect on network cost for different data rates in a ring network.

Among the studies on network design with consideration of transmission impairments, we take into account the impairments for lightpath assignment control for a low-speed optical network in [13]. With increase in channel bit rate, studies have been advanced to the high-speed transmission system $(\mathrm{data\ rate} \geq 10\ \mathrm{Gb/s})$. In this regime, the linear (such as GVD and PMD) and nonlinear impairments become more prominent. In [14], network performance, in terms of BER, was improved by trying to carry traffic through "good" fibers which have lower FWM effects. Reference [15] showed that lightpath assignment strongly depends on transmission techniques for impairment compensation. A traffic-grooming problem was investigated under signal-quality constraints. Note that, as OEO signal regeneration can mitigate impairment degradations, some studies concentrate on the strategy to locate regenerators at some nodes for cost savings [16], [17]. Such a study is based on the opaque network which is beyond the scope of our investigation here.

In this paper, we focus on an optical transparent network and investigate its connection-blocking probability, which is a major performance measure especially for dynamic traffic demands [18]. Compared with the RWA algorithms that are not impairment aware in a realistic optical network, significant improvement in network blocking can be achieved using our approaches.

The rest of this paper is organized as follows. The proposed impairment-aware RWA algorithms are presented in Section II. In Section III, we present and discuss illustrative numerical examples to evaluate our approaches. Section IV concludes this paper. The noise model used for distributed Raman amplifier is presented in the Appendix .

II. Impairment-Aware Routing and Wavelength Assignment (IRWA)

In this section, we present two IRWA algorithms. First, we introduce the network model in Section II-A. Then, in such a network, an integrated model of the proposed IRWA algorithms is introduced in Section II-B. Two important parts of the algorithms are network-layer module and physical-layer module. They are described in Section II-C and -D, respectively. Then, the characteristics of the proposed IRWAs are discussed in Section II-E.

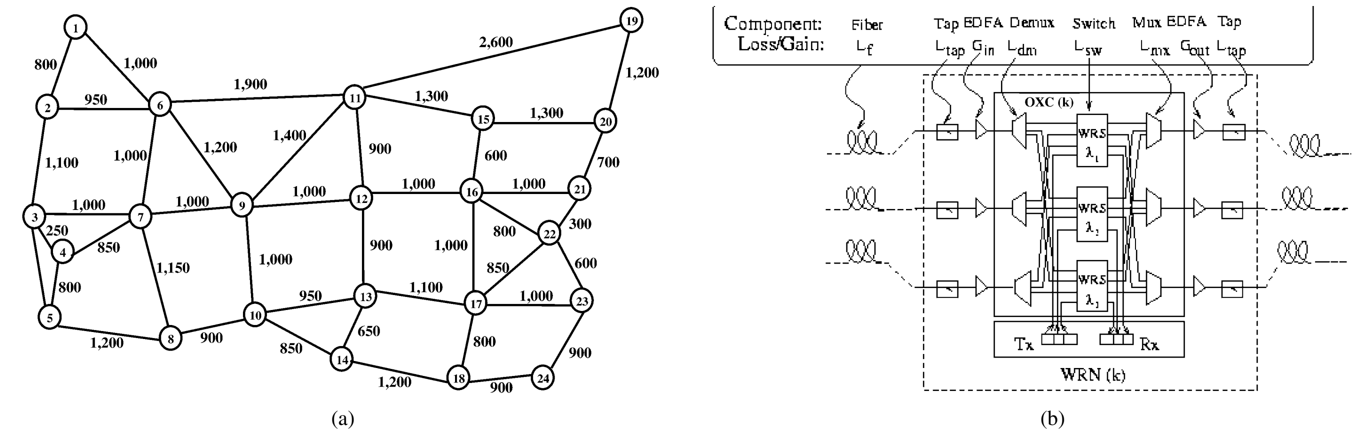


Fig. 1. (a) A sample mesh network with fiber length (in km) marked on each link. (b) Architecture of a wavelength-routing node (WRN) [7].

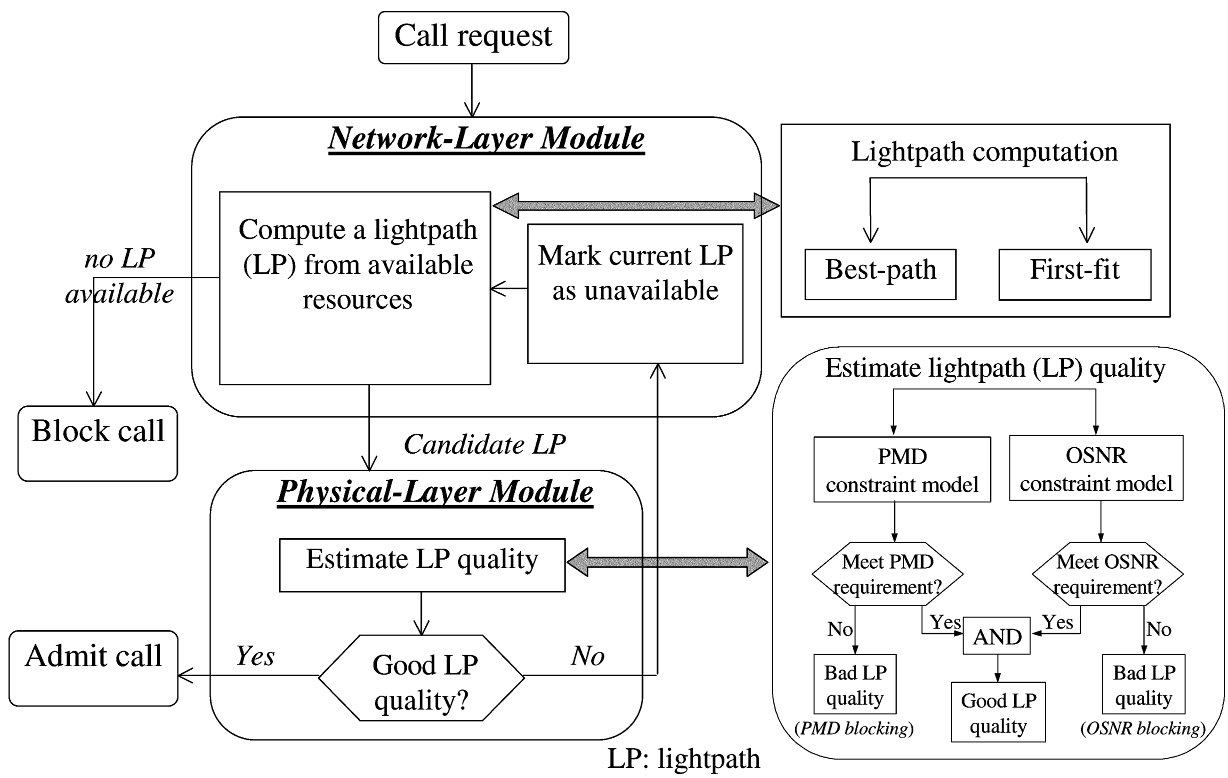


Fig. 2. Integrated model of impairment-aware RWA algorithms.

A. Network Model

The network under study is an optical transparent WDM network, which consists of multiple nodes connected by optical fibers in an arbitrary topology, as shown in Fig. 1(a). For a fiber link between two nodes, we assume that an in-line optical amplification is employed with an amplification span of 82 km. The link architecture will be discussed in detail in Section II-D2. For the present paper, each node, illustrated in Fig. 1(b), consists of an OXC and a transmitter/receiver array. The EDFAs in a node can compensate both the internal losses of the OXC and the loss of the fiber segment between the last amplification span and the OXC. The wavelength-routing switches (WRS) in the OXC are considered to employ a nonblocking active splitter/combiner architecture as in [7]. In such a network with presence of transmission impairments, upon arrival of a connection request, the source node uses a proposed RWA algorithm for lightpath computation as discussed and analyzed in the following subsections.

B. Structure of Impairment-Aware Algorithms

We take into account the effects of physical-layer impairments for network-layer connection provisioning by constructing an integrated RWA model as shown in Fig. 2. Our proposed impairment-aware RWA algorithms consist of two procedures: lightpath computation and lightpath verification. Each algorithm first uses a network-layer module to look for a candidate lightpath. If no route or wavelength is available, the call is blocked due to lack of resources in the network layer. We refer to this type of blocking as *network-resource blocking*.

If routes and wavelengths are available for the candidate lightpath, the physical-layer module is used to model the impairment effects, and compute the impairment accumulations along one of the lightpath at a time. Then, the signal quality of the candidate lightpath is estimated at the destination. If the lightpath can satisfy a certain signal-quality requirement, e.g., BER of 10^{-9} or better, the call will be admitted using this candidate lightpath. Otherwise, the physical-layer module notifies the network-layer module to reject the candidate lightpath, and the network-layer module will try to find another candidate lightpath from the available resources on another wavelength, and so forth. In this way, if no available lightpath can meet the signal-quality requirement, the call is blocked. This kind of blocking is due to poor signal quality in the physical layer, and is called *physical-layer blocking*.

C. Network-Layer Module

For a given physical network topology $PG(N, L)$, a set of auxiliary wavelength-layered topologies $WG_w(N, L)$ are created for each wavelength w, $w = 1, 2, \ldots, W$, where W is the maximum number of wavelengths supported by a fiber link, N is the set of nodes, and L is the set of bidirectional links. All wavelength-layered topology graphs (WGs) are initialized to be the same as the physical network topology graph (PG) where the link weight corresponds to the fiber length. The routing decisions are made based on these auxiliary wavelength-layered graphs.

Upon arrival of a connection request, the algorithms to compute a lightpath for the request are described as follows.

Given: Current network state $WG_w(N, L)$, $w = 1, 2, \ldots, W$; a connection request R(source, destination); and signal-quality feedback.

1) Network-layer module of impairment-aware best-path algorithm (IABP)

   a) Apply a shortest-path algorithm to find a path P_w in WG_w for $w = 1, 2, \ldots, W$. A vector of path distances is defined as $\mathrm{D} = \{\mathrm{D}_w | w = 1, 2, \ldots, W\}$. If no path is available in the wth wavelength-layered topology WGw, the D_w is set to ∞. Otherwise, D_w is the total distance of path P_w.

   b) If not all elements of D are ∞, find the minimum distance $D_m \in D$, and mark the candidate wavelength $\lambda = m$; otherwise, the call is blocked; go to ***e)***.

   c) Send the lightpath P_λ to the physical-layer module for signal-quality estimation (please see details in Section II-C), and wait for feedback from the physical-layer module.

   d) If the estimation of signal quality is "acceptable," (i) set up the call by using P_λ; (ii) update WG_λ by specifying the links used by P_λ as occupied (can be done by changing the weights of all links along path P_λ to ∞); and (iii) update the physical-layer information in the physical-layer module by recording the signal power as well as noise powers on each link along the lightpath P_λ (see details in Section II-C). Otherwise, update D_m to ∞, and go to ***b)***.

   e) Stop the procedure.

2) Network-layer module of impairment-aware first-fit algorithm (IAFF)

   a) Initialize $w = 1$, i.e., consider the first wavelength first.

   b) Apply a shortest path algorithm to find a path P_w in WG_w. If no path is available in WG_w, let $w = w + 1$ and repeat this step until we can find a path in one of the many wavelength-layered topology graphs. Mark the candidate wavelength as $\lambda = w$. If no path is available in all the wavelength-layered topology graphs WGs the call is blocked; go to ***e)***.

   c) Output the lightpath P_λ to the physical-layer module for signal-quality estimation (discussed in detail in Section II-C), and wait for feedback from the physical-layer module.

   d) If the feedback of signal quality is "acceptable," (i) set up the lightpath by using P_λ; (ii) update WG_λ by specifying the lightpath's links as occupied (can be done by changing the weight of all links along path P_λ to ∞); and (iii) update the physical-layer information in the physical-layer module by recording the signal power as well as noise powers on each link along the lightpath P_λ (please see details in Section II-C). Otherwise, let $w = w + 1$, and go to ***b)***.

   e) Stop the procedure.

When a lightpath of a connection is torn down, the link states of all links along the lightpath will be changed and need to be updated. The wavelength resources are released in the corresponding WG. The signal power and noise power are reset to zero on the wavelength channel used for this connection in the physical-layer module.

Note that the routing technique in the lightpath-computation procedure could be optimized, such as using the multiple-shortest paths technique. Using the multiple-shortest paths technique, multiple routes are computed on each WG as candidates. In the *worst case*, the shortest paths on all wavelengths have bad quality, so allowing multiple paths on each w will provide additional choices in the lightpath-computation procedure. Thus, it provides more chance to reduce the physical-layer blocking. In Section III-B, we study the computational cost for our impairment-aware algorithms. Through simulation results, we find that the worst case does not occur frequently using our proposed algorithms.

Moreover, randomly choosing a lightpath among available candidate lightpaths might reduce some interchannel impairment, e.g., channel crosstalk; however, such random-routing technique would not perform better than IABP. In IABP, for each connection request, the candidate lightpath is the shortest one among shortest paths on all wavelengths. Thus, IABP has a nature of allocating wavelengths without order, but under a certain control that chooses the lightpath with minimum distance from all available shortest paths.

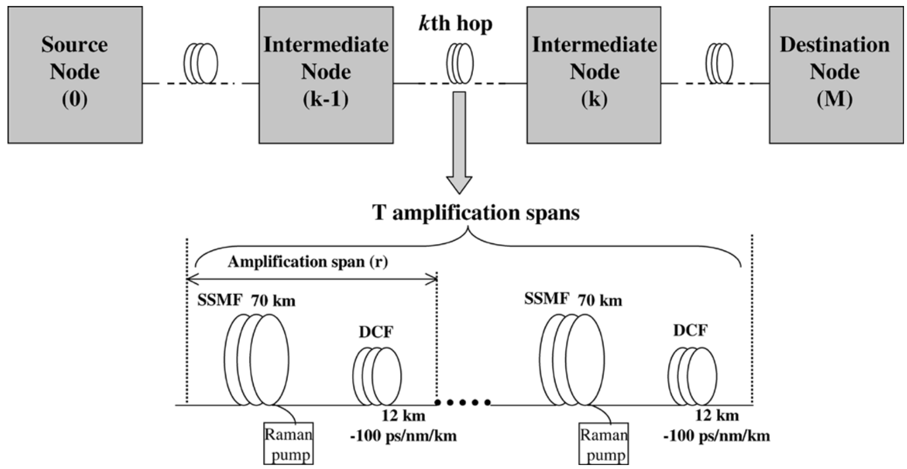


Fig. 3. Simulated lightpath architecture.

D. Physical-Layer Module

BER, which considers the effects of all the impairments, is a comprehensive criterion for evaluating signal quality. Since our focus is on the design of connection-provisioning algorithms that take the impact of impairments into consideration in a high-speed network, we consider PMD and noises (i.e., node noise including OXC crosstalk and EDFA ASE noise, and Raman-amplifier noise including ASE noise and multipath interference) as dominant factors that affect signal quality. Constraints imposed by optical signal-to-noise ratio (OSNR) and PMD effect are used in our physical-layer module to evaluate the signal quality of a connection (see Fig. 2). The lightpath computed by taking only the OSNR and PMD into consideration might not guarantee that the BER requirement would be satisfied because of other types of physical impairments. However, a lightpath not satisfying OSNR and PMD requirement will not be able to satisfy the BER requirement and should be blocked. Hence, at a minimum, OSNR and PMD must be taken into account, and we consider them here because they are the dominant impairments in a high-speed (>10 Gb/s) transmission system.

1) PMD Constraint Model: As the channel bit rate increases to 10 Gb/s and beyond, PMD becomes one of the most critical limiting problems for data transmission in a high-speed network. PMD strongly affects the transparent transmission length as [8]

$$B \times \sqrt{\sum_{k=1}^{M} D_{\mathrm{PMD}}^2(k) \times L(k)} \leq \delta \tag{1}$$

where B is the data rate; $D_{\mathrm{PMD}}(k)$ is the fiber PMD parameter in the kth hop of the transparent lightpath (in Fig. 3) consisting of M hops; and $L(k)$ is the fiber length of the kth hop. The parameter "δ," which represents the fractional pulse broadening, should typically be less than 10% of a bit's time slot for which the PMD can be tolerated [8]. This transmission-length limitation is called the *PMD constraint* in our work. If a call needs to be routed farther than this PMD limit of transmission length, it will be rejected.

The PMD constraint is a function of the fiber PMD parameter D_{PMD}; thus, different fibers, which have different values of D_{PMD}, induce different degrees of PMD constraint. In this paper, we assume all fibers have the same D_{PMD} in the network for an illustration of the role of the PMD constraint in the proposed IRWAs. A nonuniform D_{PMD} distribution among all fibers could also be considered for evaluating the proposed IRWAs, and we would expect better performance improvement on connection provisioning using our approaches. This is because our algorithms estimate a lightpath's quality according to the constraint models in the physical-layer module. With nonuniform fibers, the fiber's quality is differentiated through the PMD-constraint model. Hence, the algorithms can avoid routing lightpaths through bad-quality fibers which may lead to unacceptable signal quality of the lightpath.

2) OSNR Constraint Model: A Q factor [19] can be used as a good intermediate parameter for BER and OSNR. As an example, a BER of 10^{-9} corresponds to a Q factor equal to six with the Gaussian noise approximation while Q factor can be approximated as [20]:

$$Q = \sqrt{\frac{B_o}{B_e}} \frac{2\mathrm{OSNR}}{\sqrt{4\mathrm{OSNR}+1}+1} \tag{2}$$

where B_o is optical bandwidth and B_e is electrical bandwidth.

A lightpath's architecture as shown in Fig. 3 is used to evaluate the OSNR of the lightpath. The in-line amplifier uses the backward-pumped distributed Raman amplifier (DRA), which is a promising technique for long-haul high-speed ($\geq$ 10 Gb/s) transmission systems [21], [22]. For a fiber link between nodes k and $k+1$ on the lightpath, in-line optical amplification is employed, with an amplifier spacing of 82 km (which is a typical figure in telecom networks). Each amplification span consists of 70 km of standard single-mode fiber (SSMF) whose dispersion and dispersion slope are compensated by 12 km of dispersion-compensation fiber (DCF). The fiber attenuation of SSMF and DCF is 0.2 and 0.5 dB/km, respectively. The DRA exactly compensates for the fiber losses in an amplification span.

Efficient computation of the impact of the RWA algorithms on network performance requires a simplified physical-layer model. We, therefore, consider some optimal assumptions in this paper. In particular, we assume that the DCF completely compensates dispersion on all channels in every amplification span, and there is no accumulated dispersion along the lightpath in our system with 10-Gb/s channel rate. However, as channel rate increases to 40 Gb/s, the broadband dispersion compensation leaves residual dispersion which requires precise dispersion management [29]. The residual dispersion might accumulate and affect a lightpath's quality. It needs to be further studied for efficient network operation under such a high-speed system.

Since the OSNR on a lightpath varies with changes in network traffic, an iterative method, which is based on the current network state, is used to calculate the signal and noise powers propagating through the lightpath. For a given lightpath from a source to a destination node shown in Fig. 3, we express below the output power of signal (S), DRA's noise $(\mathrm{N_{DRA}})$, and node noise $(\mathrm{N_{node}})$, which includes crosstalk $(\mathrm{N_{xt}})$ and ASE noise of EDFA $(\mathrm{N_{EDFA}})$, at the $(k+1)$th intermediate node as the following recursive equations

$$S(k+1) = S(k)\prod_{r=1}^{T} L_{tf}(r)G_a(r,\lambda) \tag{3}$$

$$N_{\mathrm{DRA}}(k+1) = N_{\mathrm{DRA}}(k) + P_a\sum_{r=2}^{T}\left(\prod_{j=r}^{T} L_{tf}(j)G_a(j,\lambda)\right) \tag{4}$$

$$N_{\mathrm{node}}(k+1) = N_{xt}(k+1) + N_{\mathrm{EDFA}}(k+1) \tag{5}$$

with

$$N_{xt}(k+1) = N_{xt}(k)\prod_{r=1}^{T} L_{tf}(r)G_a(r,\lambda) + X_{sw}P_{xt}(k+1)$$

$$N_{\mathrm{EDFA}}(k+1) = N_{\mathrm{EDFA}}(k)\prod_{r=1}^{T} L_{tf}(r)G_a(r,\lambda) + P_{\mathrm{EDFA}}$$

where $L_{tf}(r)$ is the total loss of the SSMF and DCF in the rth amplification span of the fiber segment between nodes k and $k+1$, which consists of T amplification spans (see Fig. 3); $G_a(r,\lambda)$ is the amplifier gain of the rth span; and P_a is the noise generated by a DRA. DRA noise (ASE noise and multipath interference) models used in this paper are based on approximate models investigated in [25] and [26], and described in the Appendix ; P_{xt} is the total power of copropagating signal shared with the desired signal on wavelength λ in the switch; and the X_{sw} is the switch crosstalk ratio. The details of the switch architecture [Fig. 1(b)] and crosstalk generation are described in [7]. The P_{EDFA} is the total ASE noise[1] generated by EDFAs at the output of the node. At the destination node, the OSNR is given as

$$\mathrm{OSNR}_{\mathrm{destination}} = \frac{S(\mathrm{destination})}{\mathrm{N_{DRA}}(\mathrm{destination}) + \mathrm{N_{node}}(\mathrm{destination})} \tag{6}$$

If the accumulated noise degrades the OSNR of a lighpath to below a required threshold, the lightpath should not be used, and is blocked. The parameter values used in our constraint models are those found in typical telecom systems, and they are listed in Table I.

[1] $P_{\mathrm{EDFA}} = 2n_{sp}(G_{\mathrm{in}}-1)hf_\lambda B_o L_{dm}L_{sw}L_{mx}G_{\mathrm{out}}L_{\mathrm{tap}} + 2n_{sp}(G_{\mathrm{out}}-1)hf_\lambda B_o L_{\mathrm{tap}}$ where h is Planck's constant; other parameters are defined in Fig. 1(b) and Table I.

TABLE I
SYSTEM PARAMETERS USED IN THE MODELS

Parameter	Value
Wavelengths (in nm)	1542.6~1554.6 with 0.8nm channel spacing
Channel bit rate	10 Gbps
Optical bandwidth (B_o)	70 GHz
Signal power per channel	1 mW
Switch crosstalk ratio (X_{sw})	-25 dB
Loss of multiplexer/demultiplexer (L_{mx}/L_{dm})	-4 dB
Loss of switch (L_{sw}) (from [7])	-8 dB
Loss of tap (L_{tap})	-1 dB
Gain of EDFA in OXC(G_{in}, G_{out})	12 dB, 6 dB
ASE factor of EDFA at node (n_{sp})	1.2
Fiber PMD parameter ($D_{PMD}(k)$)	0.1 ps/(km)$^{1/2}$
Desired DRA gain	20 dB
Three pump wavelengths (in nm)	1410, 1450, and 1500
Corresponding pump powers (in W)	0.607, 0.209, and 0.01
OSNR threshold	7.4 dB (for BER = 10^{-9})
Polarization dependent factor (K_{eff})	2
Fiber loss at pump wavelengths (α_p)	0.3 dB/km
Backscattering coefficient (S_c)	0.0022

E. Characteristics of Proposed Impairment-Aware RWAs

Using the proposed impairment-aware algorithms, the connection admission is controlled by two metrics, i.e., free resources and signal quality. Hence, the algorithms enable auto-provisioning, which computes and evaluates lightpaths on demand. With impairment consideration, we not only require each call to be routed within a certain transmission length for which the effect of PMD can be tolerated, but we also require the pre-estimated OSNR at the destination node to meet a certain signal-quality requirement. Note that the proposed algorithms separate lightpath computation and lightpath verification in the network layer and physical layer, respectively. Thus, the network-layer module can compute routes with some performance optimization such as loading balancing and improving resource utilization.

In order to simplify our algorithm design and reduce its computation time, other potential impairments that are not treated here include: polarization dependent loss/gain (PDL/PDG), residual-dispersion accumulation, fiber nonlinearities, filter concatenation, power divergence, signal transient, etc. With current transmission technologies, where up to 10 Gb/s data traffic can be readily carried by each wavelength channel in today's backbone networks, the more accurate is the information from the physical-layer model, the more efficient will be the lightpath provisioning. Therefore, our algorithms, which combat some of the primary and dominant impairment effects, give a lower limit on network-performance improvement. Other algorithms could be more efficient when more physical impairments are incorporated in the lightpath-assignment procedure. It would be a challenge to determine how to combine all impairment effects and present them as an aggregate link parameter for lightpath routing since the effects from different kinds of impairments may not be additive. Moreover, some nonlinear effects on an end-to-end lightpath might not be estimatable from the link parameters along the lightpath [8].

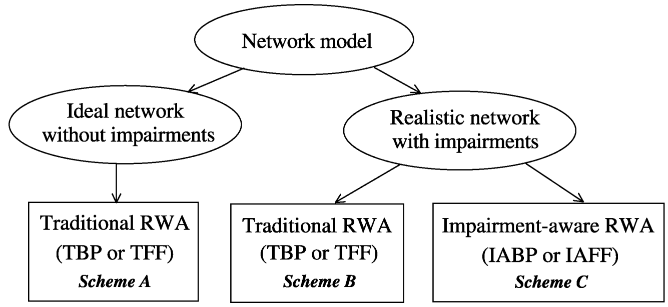


Fig. 4. Three schemes for algorithm comparisons.

When data rate increases to 40 Gb/s or higher, impairments become even more troublesome. The physical size of the transparent network is mainly limited by the impairments, requiring new transmission techniques for carrying data traffic in such higher-speed networks [2], [19]. While enabling the transfer of data traffic, with impairment consideration, the impairment-aware algorithms could make connection provisioning more efficient and hence lead to more efficient resource utilization.

III. Illustrative Numerical Examples and Discussions

We compare our proposed impairment-aware RWA algorithms (IABP and IAFF) with two impairment-unaware RWA algorithms, i.e., traditional best-path (TBP) algorithm and traditional first-fit (TFF) algorithm. TBP works as follows: (a) find an available path for every wavelength using a shortest-path algorithm; (b) if no path is available, block the call and stop; otherwise, set up the one that has minimum distance among all available lightpaths for a connection. The TFF algorithm is similar to the TBP algorithm except for wavelength assignment. In TFF, all wavelengths are numbered and checked in sequence. An available path found on the first lower-numbered wavelength will be chosen to set up a connection.

The network model under study could be an *ideal network* or a *realistic network*. In the ideal network, transmission is assumed to be error-free, i.e., network components are ideal and do not have impairments. In the *realistic* network, impairments exist due to nonideal components in the physical layer. In this paper, traditional RWA algorithms and proposed impairment-aware RWA algorithms are compared under the two above-mentioned network models. A summary of the schemes studied is shown in Fig. 4.

For illustration purposes, in our simulation experiments, we assume the network topology of Fig. 1(a); each fiber supports 16 wavelengths; dynamic traffic demands are considered where connections arrive, stay for finite holding time, and then depart; connection arrivals are Poisson and their holding times are exponential; a connection is set up with wavelength-continuity constraint; statistical results for one million calls are presented for each experiment; and other simulated parameters are provided in Table I.

A. Blocking Probability

Fig. 5 shows connection blocking probability vs. network offered load (Erlangs). It takes into account resource blocking, i.e., no free resource for setting up a connection, and physical-layer

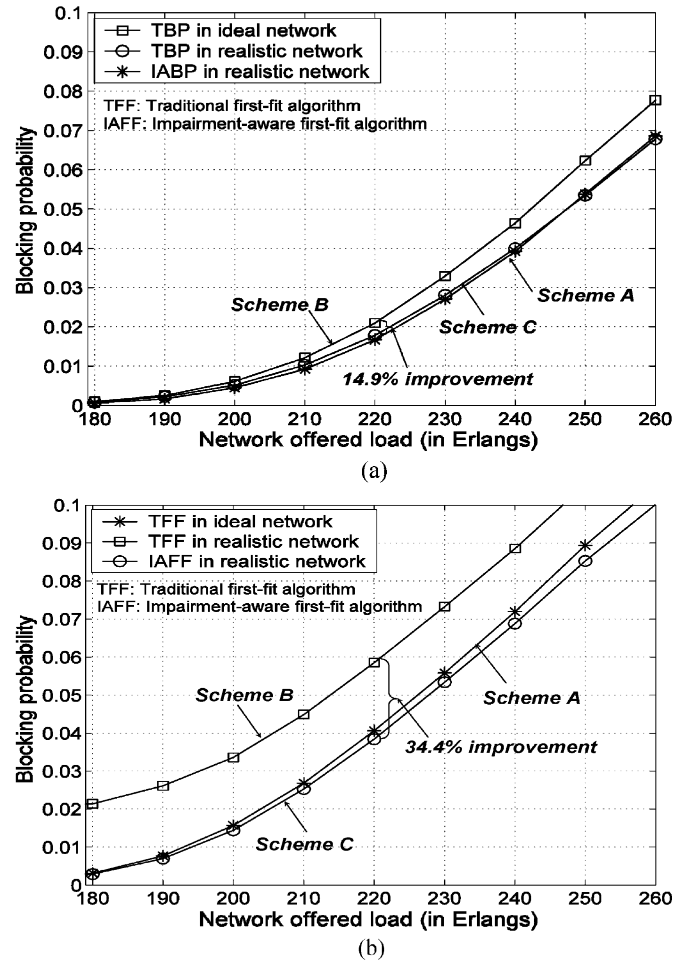


Fig. 5. Connection-blocking probability versus network offered load. (a) Best-path algorithms. (b) First-fit algorithms.

blocking, i.e., a connection cannot satisfy signal-quality requirement. The results show that: (1) impairment-unaware algorithms (TBP and TFF) have higher blocking probability in a realistic network than in an ideal network due to the effect of transmission impairments; and (2) significant improvement in blocking can be achieved by our proposed algorithms (IABP and IAFF), as compared with impairment-unaware algorithms, in a realistic network. As shown in Fig. 5, for example, at a load of 220 Erlangs, 14.9% and 34.4% improvement in blocking probability are achieved by using IABP and IAFF, respectively. This is because the proposed algorithms obtain information of a lightpath's quality from the physical layer, and they take impairment effects into consideration in the RWA stage. Hence, the algorithms automatically provision signal-quality-guaranteed connections and some unnecessary physical-layer blocking situations can be avoided. Furthermore, a lightpath with good signal quality is preferred through impairment constraints such that the network resources are under intelligent control and are used more efficiently in the impairment-aware algorithms. Finally, we also observe that blocking probabilities of our proposed algorithms are very close to those of traditional RWA in an ideal network.

Note that the impairment-aware first-fit algorithm (IAFF) has lower blocking probability than the traditional first-fit algorithm

(TFF) in an ideal network. This is because, for the traditional first-fit algorithm in an ideal network, lightpath assignment is impairment unaware, and only depends on resource availability; thus the first lightpath on the free lowest numbered wavelength will be chosen for a connection request. However, for impairment-aware first-fit algorithm (IAFF), if the current first-available lightpath does not satisfy the quality requirement, it will try to find the next available lightpath which might be shorter, and hence a better alternative for the call.

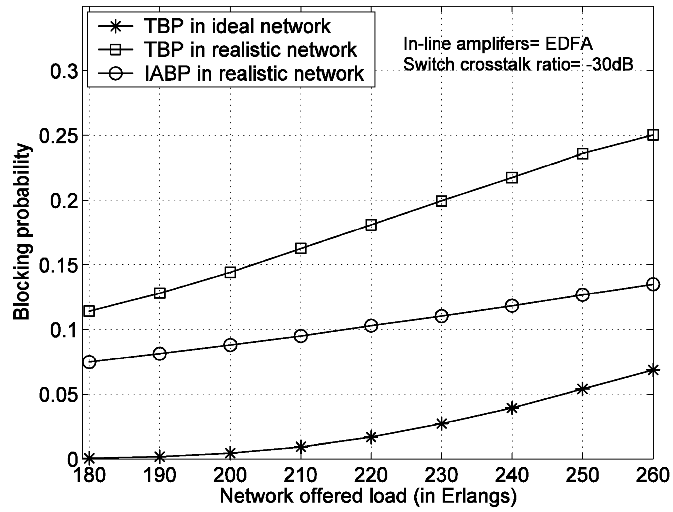
Here, we only show the results for the performance region of interest, e.g., less than 10% blocking probability. Other simulation results which consider different network topologies (such as a network with 16 nodes and 23 bidirectional links) and different number of wavelength on each link (such as 8, 32, etc.) are not shown here because of similar observations.

Besides the study of network performance discussed previously, we have also investigated the call-blocking probability for different network configurations, e.g., employing the current technology of EDFAs for in-line amplification. Instead of the DRA in Fig. 3, an EDFA which has 20-dB small-signal gain and 4-dB noise figure, is used for fiber-loss compensation in an amplification span, and each node has the crosstalk ratio of -30 dB. The simulation results are shown in Fig. 6. In this case, the proposed algorithms are not close to the result of the algorithm in an ideal network due to the limitation of transmission technology. But the blocking probability still can be significantly reduced by using the impairment-aware algorithms as compared to the traditional algorithms in a realistic network.

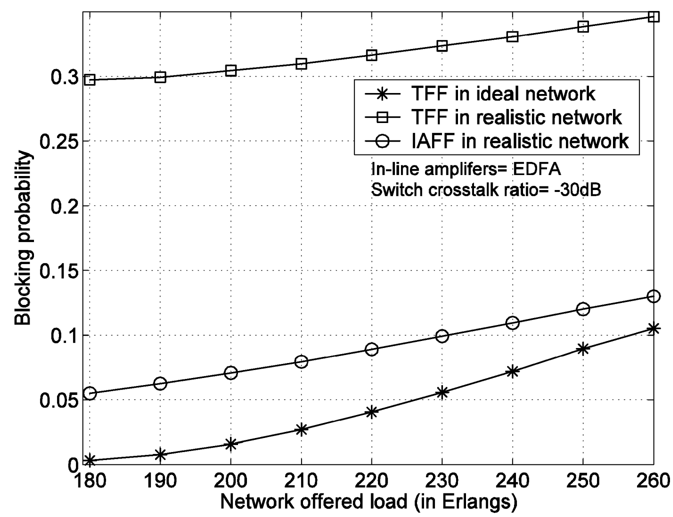
B. Computational Cost

Using impairment-aware RWA increases the computational complexity due to signal-quality estimation; however, it provides much better network performance (i.e., lower blocking as shown in Fig. 5). The tradeoffs between optimality of blocking probability and computational cost is considered here. Fig. 7 shows that the average number of trials for processing the signal-quality estimation for each call request is very close to 1 for both impairment-aware algorithms (IABP and IAFF). This means that the computational cost of signal-quality estimation is reasonable for performance improvement, i.e., for reducing blocking probability (in Fig. 5).

For a range of network offered loads, the number of trials for signal-quality estimation in our impairment-aware algorithms increases when the offered load is low, and decreases when offered load is high. This is because, in case of low traffic load, enough resources are available to ensure low call-blocking probability so that the algorithms can select alternate resources (route and/or wavelength) for call requests. However, in case of high traffic load, the call-blocking probability becomes higher due to lack of resources, which prevents the algorithms from having too many choices. For example, in Fig. 7, the simulated load range from 180 to 260 Erlangs is a low-load range for the impairment-aware best-path algorithm, but it is a high-load range, relatively speaking, for the impairment-aware first-fit algorithm. Therefore, as observed, the number of trials per call increases for the impairment-aware best-path algorithm, and decreases for the impairment-aware first-fit algorithm over this load range.



(a)



(b)

Fig. 6. (a) Connection-blocking probability for best-path algorithms employing in-line EDFA. (b). Connection-blocking probability for first-fit algorithms employing in-line EDFA.

C. Effect of Data Rate

The transmission impairments depend on the data rate. As we know, the linear and nonlinear effects become more prominent in a high-speed transmission system. With higher data rate, a higher OSNR is required, e.g., an extra 6 dB is required for increasing data rate from 10 to 40 Gb/s. When data rate increases to 20 or 40 Gb/s, PMD becomes the dominant factor for physical-layer blocking because the limited transparent-transmission length is significantly reduced based on (1). Since the sample network (Fig. 1) used in our study has a large geographical scale, most of the connections will be limited by PMD effect for bit rate ≥ 20 Gb/s. To illustrate the blocking performance of our proposed impairment-aware RWA algorithms for different channel bit rates, we study our proposed schemes for different network scales. We use a scalar $\beta(\beta \leq 1)$, with which we multiply the original length of all fiber links inside the original network in Fig. 1, to change the span of the network for our study.

In Fig. 8, we show the network scale vs. blocking probability for three different channel data rates, i.e., 10, 20, and 40

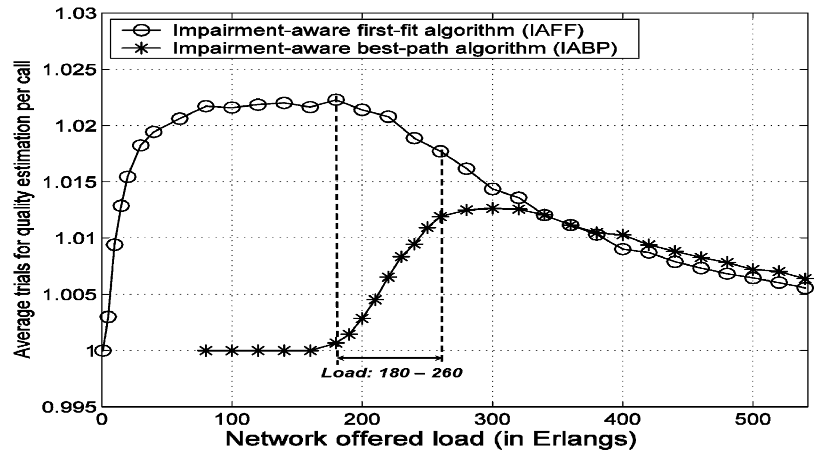


Fig. 7. Average number of trials for signal-quality estimation per call.

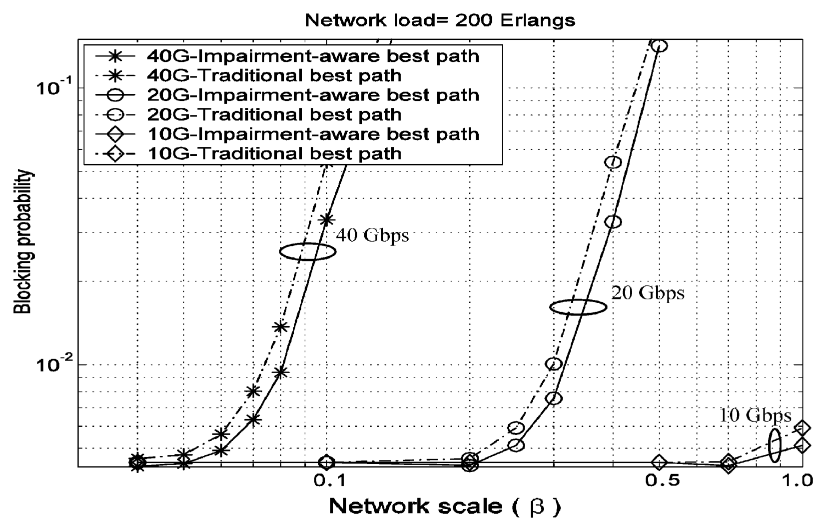


Fig. 8. Effect of channel bit rate on algorithms in a realistic network.

Gb/s, using our proposed impairment-aware best-path RWA algorithm (IABP) and traditional best-path RWA algorithm (TBP). Results show that blocking probability for 40-Gb/s data channel increases very fast when the network scale increases, whereas the blocking probability for 10 Gb/s increases much slower when network size increases. This also indicates that the network may need new transmission technologies to enable it to carry high-speed data traffic. Overall, while enabling data traffic, the blocking probabilities for our proposed algorithm (IABP) are smaller than that of the traditional RWA algorithm (TBP) in a realistic network for all three different channel data rates.

IV. Conclusion

This paper investigated new algorithms for efficient connection provisioning with signal-quality guarantees in an all-optical WDM mesh network operating with high-speed wavelength channels. Under high-speed data rate, the impact of transmission impairments on a lightpath's quality can become very prominent, requiring appropriate techniques in both the physical layer and the network layer to mitigate the impairment effects on network performance. Therefore, focusing on network-layer techniques, our study developed a novel hierarchical RWA model where the OSNR and PMD effect were estimated in the physical layer, and regarded as metrics for high-speed connection provisioning in the network layer. Such impairment-aware-RWA algorithms automatically consider the effects of impairments when setting up a lightpath. The major network performance of connection-blocking probability was measured under different in-line amplification scenarios including all-DRA and all-EDFA amplifications. The computational cost of the proposed algorithms was evaluated, and the effects of channel bit rate were studied. With signal-quality consideration, as compared to algorithms that are not impairment aware in a realistic optical network, our proposed impairment-aware algorithms efficiently provide signal-quality-guaranteed connections while significantly reducing connection-blocking probability, better utilizing network resources, and having a reasonable computational requirement.

Appendix
DRA Model

A fiber-based Raman amplifier uses intrinsic properties of the silica fiber for amplification which is produced by stimulated Raman scattering (SRS) [19]. When the same fiber used for signal transmission is also used for signal amplification, it is called *distributed Raman amplification*.

Raman amplifier has been investigated experimentally and theoretically [21]–[28]. Some key factors which need to be considered in designing a Raman amplifier include: amplifier spontaneous noise, Rayleigh scattering, interaction between pumps and signals (pump-pump, pump-signal, and signal-signal interactions), and pump depletion (saturation). A mathematical model to simulate the physical properties that affect these factors was developed by Kidorf, *et al.* [21]. Some simplified models can approximate the amplifier behavior, such as fiber loss and ASE noise [23], [25]; multipath interference [23], [26], [27]; as well as SRS and its temperature dependence [27].

Our impairment-aware RWA algorithms require a reasonable amplifier model to simulate the most significant impairments from actual devices. The most important factors that limit the performance of distributed Raman amplifiers are Rayleigh scattering and Raman amplified spontaneous emission (ASE) [19], [23], [24]. To simplify our algorithm design and reduce its computation time, we capture the effects of ASE and double Rayleigh scattering (multipath interference) in our simulated DRA model in much the same way as in [25] and [26]. They are summarized here for easier reference. The DRA model assumes that: 1) fiber losses for all pump lights are identical; 2) the energy losses, when a high-frequency photon is transformed into a low-frequency photon, are neglected; 3) small-signal case is considered for which gain and noise for each wavelength are independent of the number of signal wavelengths; and 4) the pump depletion caused by signal-pump coupling is negligible. Since the pump supplies energy for signal amplification, it depletes as signal power increases. As can be seen from

$$g(\omega) = g_R(\omega)\left(\frac{P_{\text{pump}}}{a_{\text{pump}}}\right) \tag{7}$$

where g is the optical gain, g_R is Raman-gain coefficient, and a_{pump} is the cross-sectional area of the pump beam inside the fiber, the optical gain reduces when the pump power decreases. This reduction in gain is referred to as gain saturation [19]. Since pump power is typically much larger than channel signal power, the Raman amplifier operates in the unsaturated regime [19].

A. Gain and ASE Noise of Distributed Raman Amplifier

For a Y-wavelength backward-pumped DRA, we assume that the signal lightwaves and the pump lightwaves are launched into each amplification span (r) at the location $z = 0$ and at $z = L$, respectively. The power evolution of pump u, $P_u(z)$, is given by

$$\frac{dP_u(z)}{dz} = \alpha_p P_u(z) - P_u(z)\sum_{i=1}^{Y}(f_i - f_u)P_i\frac{g_{ui}}{K_{\text{eff}}A_{\text{eff}}(f_i - f_u)} \tag{8}$$

where α_p is the fiber loss at pump wavelength; A_{eff} is the fiber effective area; g_{ui} is the Raman gain coefficient between pump u and pump i at frequency f_u and f_i, respectively; K_{eff} is the polarization dependent factor; and Y is the number of pumps for amplification. g_{ui} is assumed to have a gain profile which closely approximates the measured Raman-gain profile in [28]. The pump power along the fiber, $P_u(z)$, can be derived by integrating (8) with respect to z.

In the small-signal case, according to [25], at fiber length L, the small-signal optical gain $G_w(L)$, and the ASE noise power $P_{ASE}(L)$, for the wth WDM channel can be expressed as follows:

$$G_w(L) = \exp\left\{\int_0^L B_w(z)dz\right\} \quad \text{with}$$
$$B_w(z) = -\alpha_s + \sum_{j=1}^{Y}\frac{g_{wj}}{K_{\text{eff}}A_{\text{eff}}}P_j(z) \tag{9}$$

$$P_{\text{ASE}}(L) = \int_0^L C_w(z)\exp\left\{\int_z^L B_w(z_1)dz_1\right\}dz \quad \text{with}$$
$$C_w(z) = \sum_{i=1}^{Y}\frac{g_{wi}}{2A_{\text{eff}}}\left[h\nu_w\Delta_\nu\left(1 + \frac{1}{\exp\left(\frac{h(f_i - f_w)}{KT}\right) - 1}\right)\right] \cdot P_i(z) \tag{10}$$

where α_s is the fiber loss at signal frequency ν_w; subscript w refers to the wth signal light; and h is Planck's constant.

B. Multipath Interference (MPI) in Distributed Raman Amplifier

An approximate analytical model [26] is used to calculate the double-Rayleigh scattering (DRS) power. The transmission fiber used for Raman amplification is considered as a sum of the effective length L_g, which provides the gain, and the remainder length L_l, which has fiber loss. Hence, the signal-to-DRS ratio, denoted as MPI [26], is given by

$$MPI(G_R) = MPI_{L_g}(G_R) + MPI_{L_l}$$

with

$$MPI_{L_g}(G_R) = \left(\frac{S_c\alpha_s}{2C_g}\right)^2[e^{2C_gL_g} - 1 - 2C_gL_g]$$
$$MPI_{L_l} = \left(\frac{S_c}{2}\right)^2[2L_l\alpha_s - 1 + e^{-2\alpha_sL_l}]$$
$$C_g = \frac{\ln G_R - \alpha_sL_g}{L_g} \tag{11}$$

where MPI_{Lg} and MPI_{Ll} are the MPI in the effective length and fiber-loss length, respectively; S_c is the backscattering coefficient; C_g is the gain coefficient; and G_R is the Raman gain added to the fiber, i.e., the on-off gain of DRA. The on-off gain is defined as the output signal power when pumps are on divided by the output signal power with pumps off [23], [26].

A key issue in the design of a broad-band amplifier is gain flattening. For DRAs, multiple pumps can be used to flatten the gain spectrum so that all signal channels could have the same

MPI penalty. In our simulation model, the transmission fiber acts as a DRA and requires 70 km, and the DRA should provide a 20-dB on-off gain within the signal wavelength range from 1542.6 to 1554.6 nm. To achieve this design requirement, we use a semiexhaustive search to select the frequencies and powers for the pump lights. We set a wide range of possible frequencies and powers for the pump signals, and coarse spacing of sample values; then, the gain is calculated according to (9) for all samples. The pump signals with the minimum gain ripple, which is defined as in [25], were determined as the optimal one to meet our requirements.

Based on our optimization, three pump wavelengths are set to be 1410, 1450, and 1500 nm, and the corresponding pump powers are 0.607, 0.209, and 0.01 W, respectively. The gain ripple is 0.089, which is less than that in [25]. Using these pump signals, the Raman gain, ASE noise, and MPI noise can be calculated according to (9), (10), and (11), respectively. Since the pump power is larger than the signal power, the calculated gain and noise for each wavelength are assumed to be independent of the number of signal wavelengths existing in the DRA for simplicity, and they are put into a profile used in the physical-layer module.

The signal power, ASE power, and MPI power are examined at the DRA output when the input signal power is 0 dBm. We find that the gain of the DRA is 6 dB, i.e., 20-dB on-off gain, within the interesting wavelength range, which meets the design goal for our DRA model. Also, these results show that ASE noise is the dominant noise and is about 10 dB larger than the MPI noise for the designed 70-km DRA.

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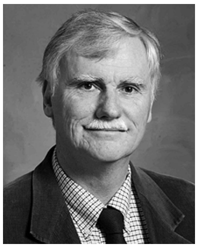

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