Signal-Quality Consideration for Dynamic Connection Provisioning in All-Optical Wavelength-Routed Networks

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ABSTRACT

We investigate new connection-provisioning algorithms to efficiently provide signal-quality-guaranteed connections in an all-optical WDM mesh network. In the all-optical network, signal degradations incurred by non-ideal transmission medium accumulate along a lightpath. When the signal degradation reaches a certain level, the connection is not usable and is blocked due to transmission impairments in the physical layer. To ensure high service quality of provisioned connections, it is essential to develop intelligent routing and wavelength assignment (RWA) algorithms which can combat the effects of impairments when setting up a connection. For this purpose, we propose two impairment-aware RWA algorithms, namely *impairment-aware best-path* (IABP) algorithm and *impairment-aware first-fit* (IAFF) algorithm. The optical signal-to-noise ratio (OSNR) requirement and polarization mode dispersion (PMD) effect are used as signal-quality constraints to avoid setting up a connection with unacceptable quality due to the effects of transmission impairments. With the 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 connection while significantly reducing connection-blocking probability, better utilizing network resources, and having a reasonable computational requirement. Also, the effect of channel bit rate is studied in this paper.

KEYWORD: All-optical WDM network, impairment-aware RWA, routing and wavelength assignment, signal quality, transmission impairment.

1. INTRODUCTION

The all-optical transparent network is a promising candidate for the next-generation backbone network to provide large bandwidth at low cost. In such networks, a connection is set up via an all-optical WDM channel called a *lightpath*. Data signal of a lightpath is transmitted totally in the optical domain without any need for optical-to-electrical conversion/regeneration from source to destination, and this is called the transparency property of optical networks. Setting up a lightpath for a connection request by using a routing and wavelength assignment (RWA) technique [1] is known as connection provisioning. Intelligent connection provisioning is an important issue for minimizing cost and better utilizing network resources.

A large amount of connection-provisioning problems have been investigated under the assumption that the optical medium is an ideal one to transmit data signal 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. However, transmission impairments, present in fibers and optical components, may significantly affect the quality of a lightpath [3, 4], and, hence, they must be taken into consideration during connection provisioning.

In particular, because of transparency of an optical network, noise and signal distortions due to linear and nonlinear effects accumulate along the lightpath and may cause significant signal degradation [2, 3]. 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; we call this phenomenon *physical-layer blocking*. When provisioning connections based on impairment-unaware RWA algorithms, transmission impairments are not considered during lightpath assignment. As a result, a lightpath, which cannot meet the requirement of signal quality, might be set up. Therefore, the control plane of an all-optical network must incorporate characteristics of the physical layer in setting up a lightpath for a new connection.

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The transmission impairments induced by non-ideal transmission components can be classified into categories: linear and nonlinear. Some important linear impairments are amplifier noise, fiber 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 effects are independent of signal power and might be handled as a constraint on routing [11]. The nonlinear effects are significantly more complex. Moreover, an analytical model for some nonlinear effects is not readily available at the moment [10, 18].

The goal of this paper is to assess the impacts of transmission impairments, and take them into consideration in the design of connection-provisioning algorithms to guarantee the signal quality of a connection. Hence, instead of considering all impairments in a transmission system, our study is based on the assumption that (a) the impairments of a transmission system are Raman amplifier noise, PMD and crosstalk at OXCs which are significant linear impairments in high-speed (≥ 10 Gbps) networks [9, 11]; and (b) GVD can be adequately compensated on a per-link basis. To take into account the effects of these impairments to ensure the signal quality of a connection, we propose impairment-aware RWAs, called *impairment-aware best-path (IABP) algorithm* and *impairment-aware first-fit (IAFF) algorithm*, for a bit rate of 10 Gbps or higher in a typical nationwide mesh network shown in Fig. 1(a). With the signal-quality consideration, as compared to the 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. Also, the effect of channel bit rate is studied in this paper.

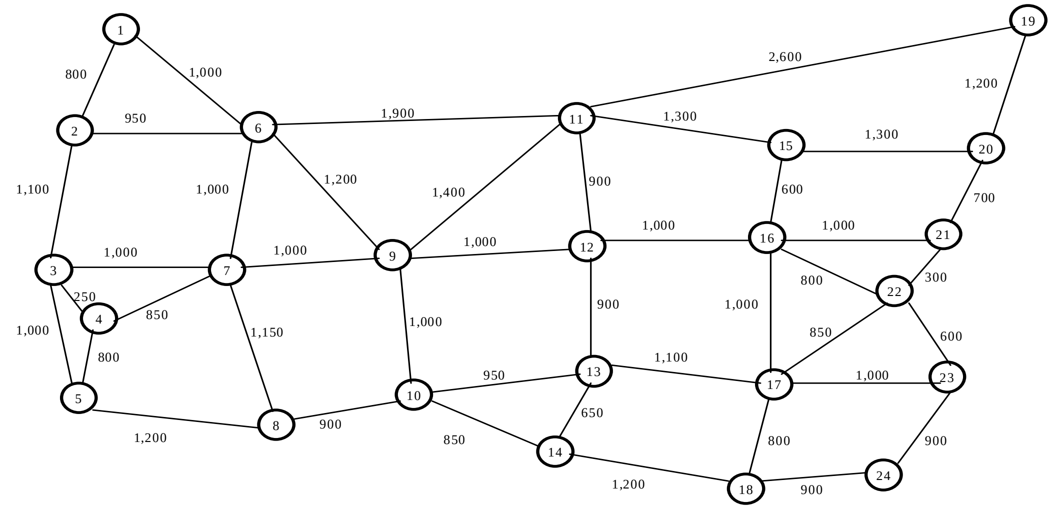

Fig. 1(a). A sample mesh network with fiber length (in km) marked on each link.

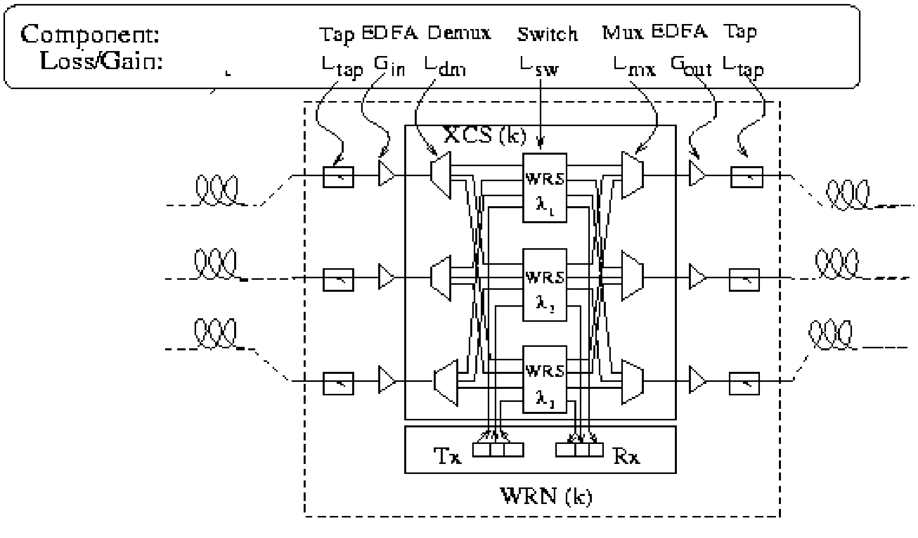

Fig. 1(b). Architecture of a wavelength-routing node.

2. RELATED WORKS AND OUR CONTRIBUTION

The study of the transmission impairments in an all optical-network is now attracting more attention from researchers for different network-design problems [3-7]. There are two foci in these research works: effects of impairments on the performance of traditional RWA [3, 4], and network design with impairment considerations [5-8]. The studies in paper [3, 4] show that the network performance can be significantly affected by transmission impairments. Among the studies involving low-speed transmission (data rate $\leq$ 2.5 Gbps) where some linear impairments (such as amplifier noise, switch crosstalk, etc.) could be dominant effects, reference [8] used a BER-constrained RWA to optimize the regeneration-resource utilization in a translucent network where OEO transformation is employed at some nodes. And in reference [5], we take into account the impairments for lightpath assignment control. With increase in channel bit rate, in a high-speed transmission system (data rate $\geq$ 10 Gbps), the linear (such as PMD, GVD, etc.) and nonlinear impairments become more prominent [9, 11], and thus new techniques are necessary for impairment compensation [15]. Based on this ground, the effects of impairments have been considered for traffic grooming in reference [6] and for regenerator savings in reference [7]. However, incorporating high-speed transmission impairments into signal-quality consideration for connection provisioning has not been developed in detail, until now.

Therefore, we investigate impairment-aware RWA algorithms which take the impairment effects into account when provisioning a connection in a transparent high-speed (10 Gbps or higher) network. The signal-to-noise ratio (OSNR), a major contributor to BER, is a suitable criterion to evaluate the signal quality of a connection. Thus, OSNR requirement and PMD effect are used as constraints in our approaches to guarantee the signal quality of a connection. Such algorithms enable efficient auto-provisioning which compute and evaluate a lightpath for a connection on demand.

3. IMPAIRMENT-AWARE ROUTING AND WAVELENGTH ASSIGNMENT (IRWA)

In this section, we propose two impairment-aware RWA (IRWA) algorithms called impairment-aware best-path (IABP) algorithm and impairment-aware first-fit (IAFF) algorithm. A high-level structure of the proposed impairment-aware RWA algorithms is presented in Fig. 2. Two major function modules, network-layer module and physical-layer module, are presented in Subsection A and B, respectively.

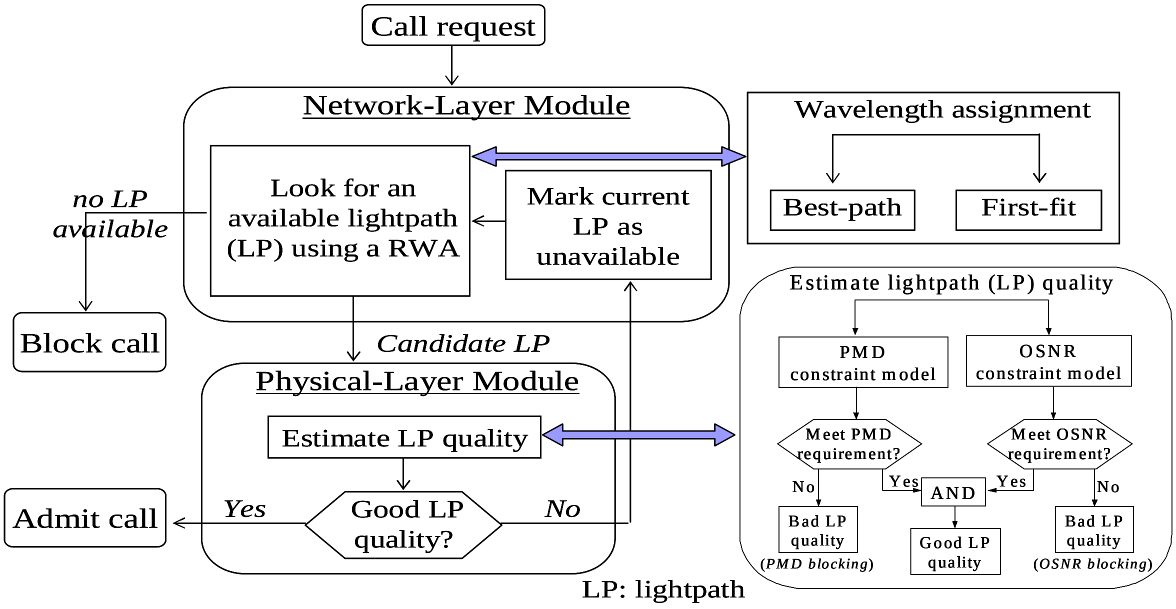

Fig. 2. Impairment-aware RWA algorithms.

3.1 Network-Layer Module

For a given physical network topology $PG(N, L)$, a set of auxiliary wavelength-layered topologies $WG_k(N, L)$ are created for each wavelength k, $k = 1, 2, \dots, W$, 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 bi-directional 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.

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

Step 1*:* For the given source and the destination nodes of a call request, find the shortest path P_k in WG_k using a shortest-path algorithm, e.g., Dijkstra's algorithm, for $k = 1, 2, \dots, W$. A vector of path distances is defined as $D = \{D_k \mid k = 1, 2, \dots, W\}$. If no path is available in the kth wavelength-layered topology WG_k, D_k is set to ∞. Otherwise, D_k is the total distance of path P_k.
Step 2*:* 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 ***Step 5***.
Step 3*:* Send the lightpath P_λ to physical-layer module for signal-quality estimation (please see details in Section III-B), and wait for feedback from physical-layer module.
Step 4*:* If the feedback of signal quality is "acceptable", set up the call by using P_λ; update WG_λ by specifying the links used by P_λ as occupied (can be done by changing the weights of all links along the path P_λ to ∞); at the same time, update the physical-layer information for the current network state. Otherwise, update D_m to ∞, and go to ***Step 2***.
Step 5*:* Stop the procedure.

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

The IAFF algorithm is similar to IABP algorithm except for the network-layer module. In IAFF, all wavelengths are numbered and checked in sequence; and the lightpath with first lower-numbered wavelength as well as acceptable signal quality is chosen for setting up a connection. This contrasts the IABP algorithm which selects the lightpath with acceptable signal quality as well as the minimum distance among all available paths for all wavelengths.

3.2 Physical-Layer Module

Bit-error rate (BER), which considers effects of all impairments, is a comprehensive criterion for evaluating signal quality. Since our focus is on the design of connection provisioning that combats impairments in a high-speed network, we assume polarization mode dispersion (PMD) and noises (i.e., OXC crosstalk and Raman-amplifier noise including ASE noise and multipath interference) as 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 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 the minimum, OSNR and PMD must be taken into account.

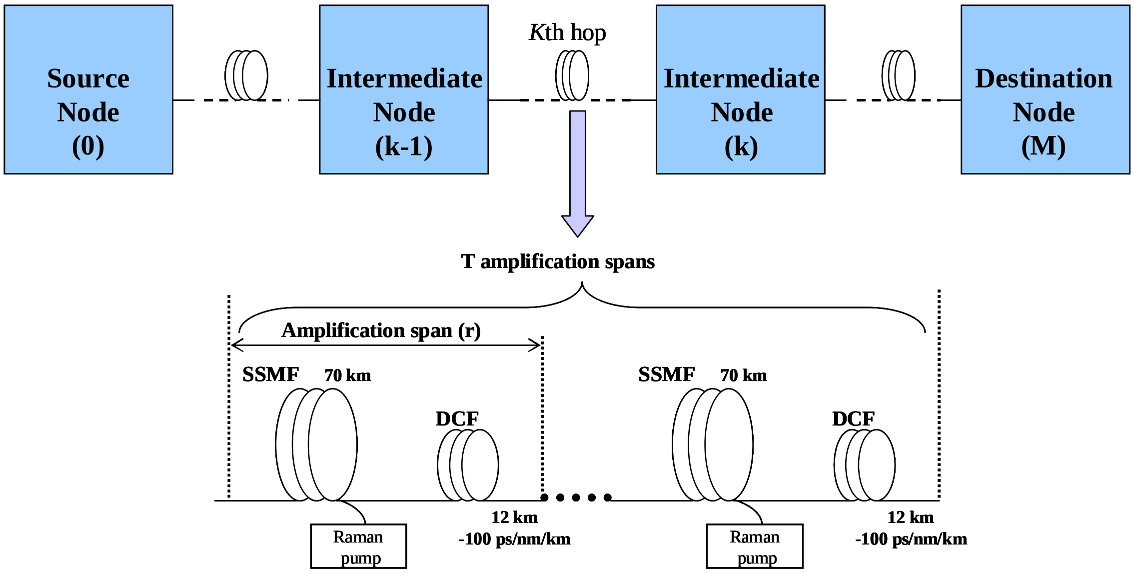

Fig. 3. Simulated lightpath architecture.

3.2.1 Polarization-mode- dispersion (PMD) constraint model

As the channel bit rate increases to 10 Gbps 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 [11]:

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

where B is the data rate; $D_{PMD}(k)$ 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 "α", 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 [11]. 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.

3.2.2 Optical signal-to noise ratio (OSNR) constraint model

A Q factor [15] can be used as a good intermediate parameter for BER and OSNR [12]. 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 [12]:

$$Q = \sqrt{\frac{B_o}{B_e}} \frac{2\,OSNR}{\sqrt{4\,OSNR + 1} + 1} \qquad (2)$$

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 (≥ 10 Gbps) transmission systems [13, 14]. 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. Each amplification span consists of 70 km of standard single-mode fiber (SSMF) whose dispersion and dispersion slope are completely compensated by 12 km of dispersion-compensation fiber (DCF). The fiber attenuation of SSMF and DCF is 0.2 dB/km and 0.5 dB/km, respectively. The DRA exactly compensates for the fiber losses in an amplification span. Both the internal losses of the OXC and the loss of the fiber link between the last DRA and the OXC are compensated by the EDFAs at the node (see Fig. 1(b)).

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 power propagating through the lightpath. For a given lightpath from a source to a destination node shown in Fig. 3, we express the output power of signal (S), DRA's noise (N_{DRA}), and node noise (N_{node}), which includes crosstalk (N_{xt}) and ASE noise of EDFA (N_{EDFA}), at the $(k+1)$th intermediate node as the following recursive equations:

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

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

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

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

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

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); $G_a(r)$ is the amplifier gain of the rth span; and P_a is the noise generated by a DRA (Due to space limitation, we will not elaborate the DRA-noise (ASE noise and multipath interference) models used in this work. The models are based on approximate models investigated in [16, 17]); P_{xt} is the total power of co-propagating 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 [4]. The P_{EDFA} is the total ASE noise* generated by EDFAs at the output of the node. At the destination

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

node, the OSNR is given as:

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

If the accumulated noise degrades OSNR of a lighpath to below a required threshold, the lightpath should not be used, and is blocked.

To summarize this section, in our impairment-aware RWA algorithms, multiple metrics are used for call-admission control, e.g., the criterion of resource acceptability depends not only on free resources but also on the lightpath's signal quality. To set up a signal-quality-guaranteed connection, 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 be higher than a certain requirement. While considering PMD and OSNR, some new techniques such as dispersion compensation fiber (DCF) and distributed Raman amplifier (DRA) are employed to mitigate the impact of linear and nonlinear impairments in our work. Other impairments are not investigated here for the purposes of reducing the computation time and design complexity. However, the proposed impairment-aware RWA approaches could also be applied when more impairments must be taken into consideration. The parameters used in our constraint models are listed in Table 1.

4. 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. In TBP, (a) find an available path for every wavelength using 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.

A summary of schemes compared in this paper is shown in Fig. 4 for dynamic traffic situation, where connections arrive, stay for finite holding time, and then depart. An *ideal* network refers to a network in which transmission is error-free, i.e., network components are ideal and do not have impairments. However, in a *realistic* network, impairments exist due to non-ideal components in the physical layer. Traditional RWA algorithms and our proposed impairment-aware RWA algorithms are studied under the two above-mentioned network models.

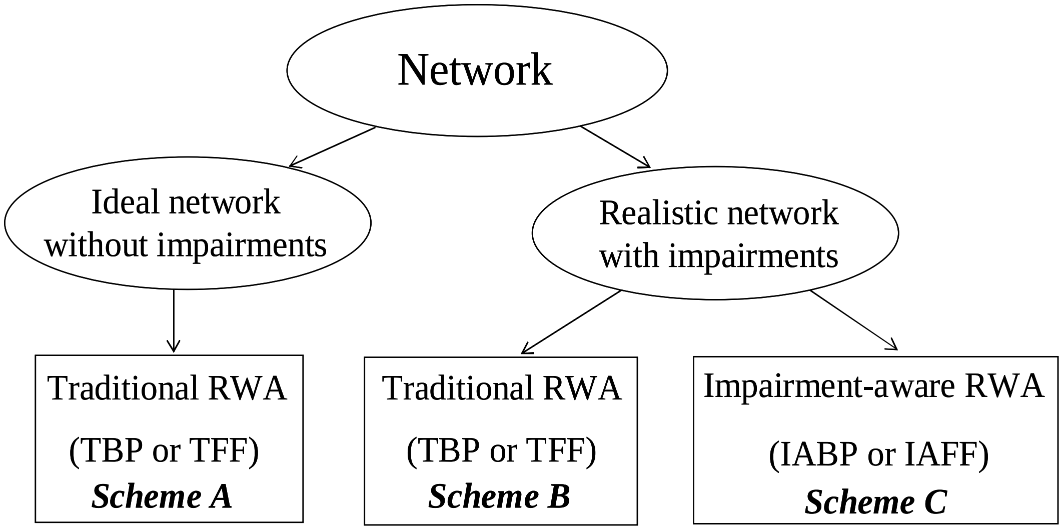


Fig. 4. Three schemes for algorithm comparisons.

For illustration purposes, in our simulation, we assume the network topology of Fig. 1(a); each fiber supports 16 wavelengths; connection arrivals are Possion and their holding times are exponential; a connection is set up with wavelength-continuity constraint; and other simulated parameters are provided in Table 1.

TABLE 1

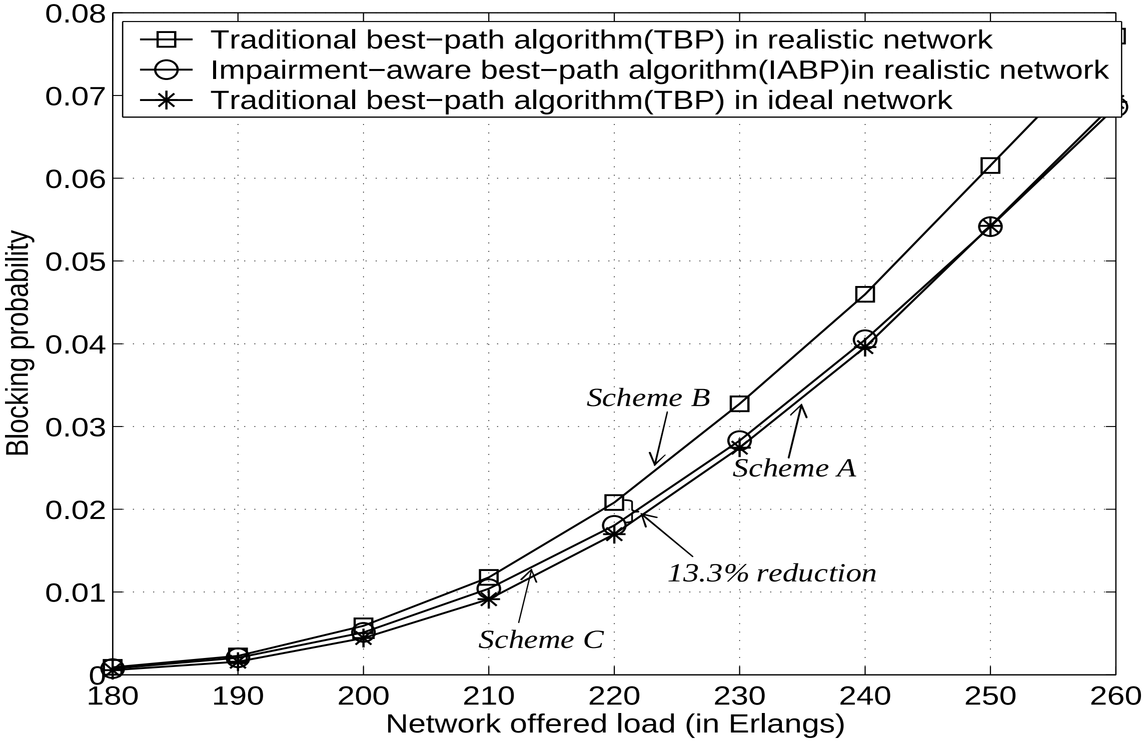
SYSTEM PARAMETERS USED IN THE MODELS

Parameter	Value
Number of wavelengths	16
Wavelengths (in nm)	1570~1585 with 1nm wavelength-spacing
Channel bit rate	10 Gbps
Optical bandwidth (B_o)	70 GHz
Signal power per channel	1 mW
Switch crosstalk ratio (X_{sw})	-30 dB
Loss of multiplexer/demultiplexer (L_{mx}/L_{dm})	-4 dB
Loss of switch (L_{sw}) (from [4])	-8 dB
Loss of tap (L_{tap})	-1 dB
Gain of EDFA (G_{in}, G_{out})	12 dB, 6 dB
ASE factor of EDFA at node (n_{sp})	1.2
Pulse broadening factor (α)	0.1
Fiber PMD parameter ($D_{PMD}(k)$)	0.1 ps/(km)$^{1/2}$
Desire DRA gain	20 dB
Three pump wavelengths (in nm)	1420, 1470 and 1480
Correspondent pump powers (in W)	0.408, 0.01 and 0.209
OSNR threshold	7.4 dB (BER = 10^{-9})
Polarization dependent factor (K_{eff})	2
fiber effective area (A_{eff})	50 μm^2
Fiber loss at pump wavelengths (α_p)	0.3 dB/km
Backscattering coefficient (S_c)	0.0022

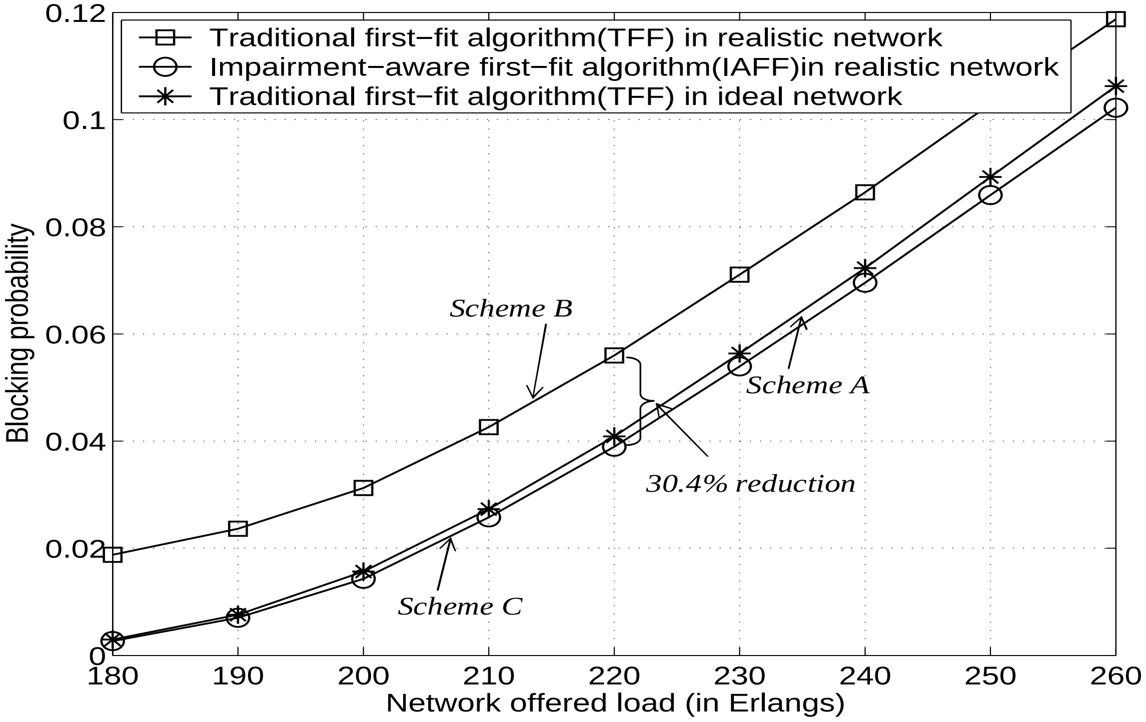
4.1 Simulation Results – Blocking Probability

Figure 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 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 reduction in blocking can be achieved by our proposed impairment-aware algorithms (IABP and IAFF), as compared with impairment-unaware algorithms, in a realistic network. As shown in fig. 5, for example, at the 220 Erlangs network load, 13.3% and 30.4% reduction in blocking are achieved by using IABP and IAFF, respectively. This is because impairments are taken into consideration in the RWA stage, and only lightpaths with good signal quality can be used to set up connections. Hence, some unnecessary physical-layer blocking situations are avoided. Furthermore, by using impairment-aware RWAs, network resources are under intelligent control and are used more efficiently. Finally, 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, the first lightpath on the available lowest-numbered wavelength will be chosen to set up the call no matter whether it can meet the signal-quality requirement or not. 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.



(a) Best-path algorithms.



(b) First-fit algorithms.

Fig. 5. Connection-blocking probability vs. network offered load.

4.2 Simulation Results – Computational Cost

In a realistic network, using impairment-aware RWA for connection provisioning increases the computational complexity due to signal-quality estimation; however, it provides much better quality of service for call requests (i.e., lower blocking in Fig. 5). The tradeoffs between optimality of blocking probability and computational cost need to be considered. Hence, we examine the average number of trials of signal-quality estimation using our proposed impairment-aware RWAs for each call request. Statistical results for one million calls are presented in Fig. 6.

Figure 6 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).

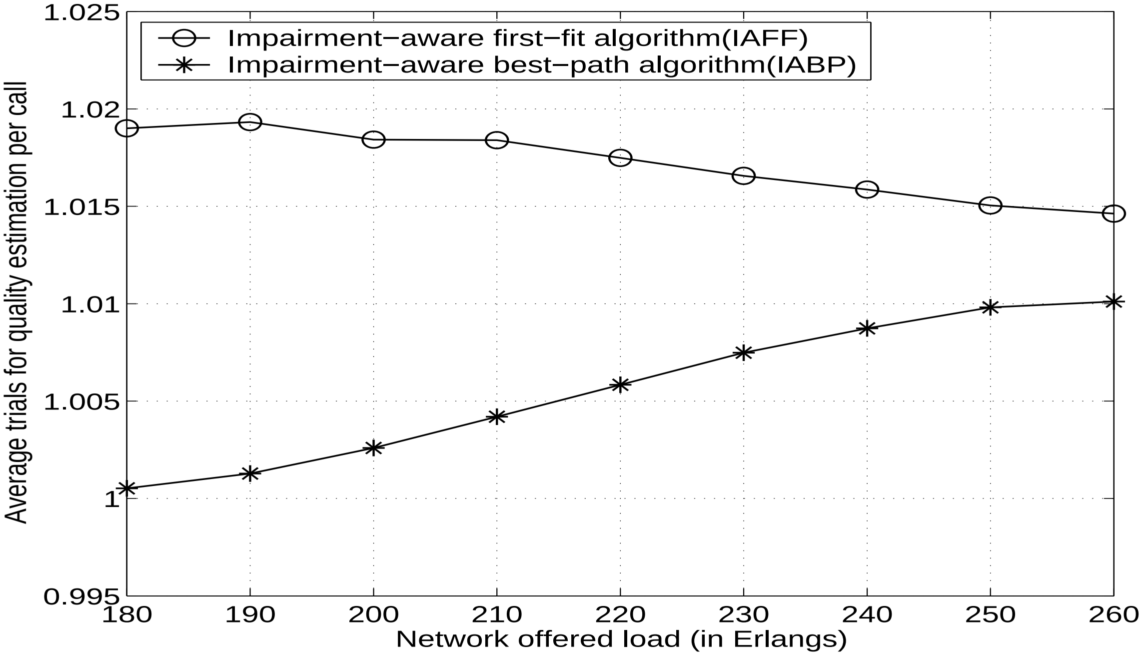


Fig. 6. Average number of trials for signal-quality estimation per call.

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 prevent the algorithms from having too many choices. In Fig. 6, the simulated load range from 210 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.

4.3 Simulation Results – 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. When data rate increases to 20 Gbps or 40 Gbps, PMD becomes the dominant factor for physical-layer blocking because the limited transparent-transmission length is significantly reduced based on Eqn. (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 Gbps. 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 β (β ≤ 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. 7, we show the network scale vs. blocking probability for three different channel data rates, i.e., 10 Gbps, 20 Gbps, and 40 Gbps, using our proposed impairment-aware best-path RWA algorithm (IABP) and traditional best-path RWA algorithm (TBP). Results show that blocking probability for 40 Gbps data channel increases very fast when network scale increases, whereas the blocking probability for 10 Gbps increases much slower when network size increases. Overall, 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 rate.

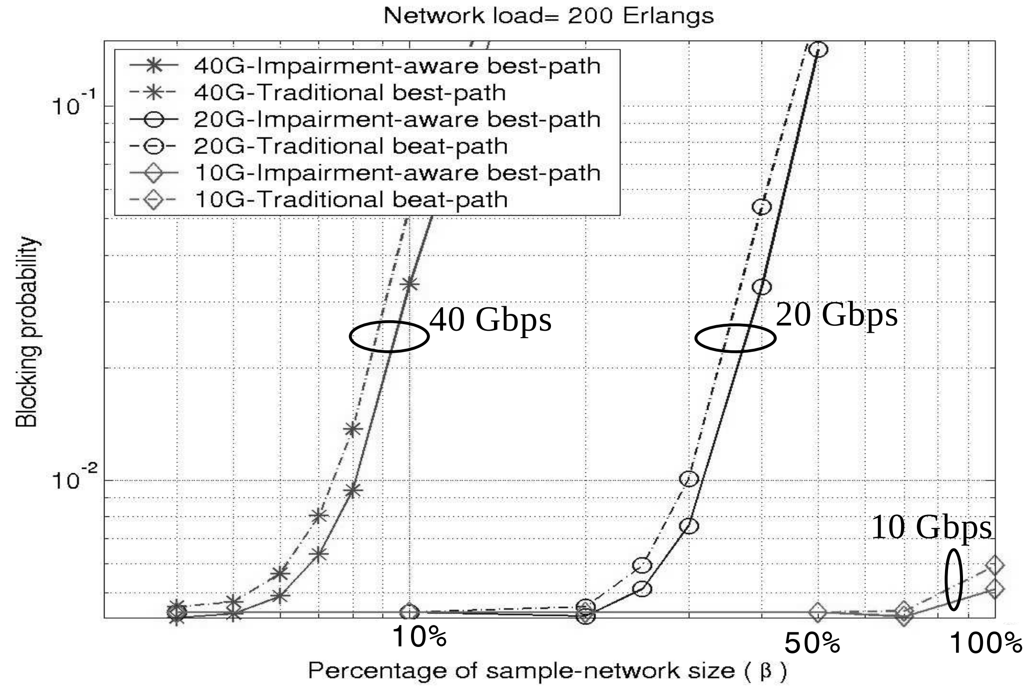


Fig. 7. Effect of channel bit rate on algorithms in a realistic network.

5. CONCLUSION

This study was devoted to the design of dynamic connection provisioning which combats transmission impairments in an all-optical WDM network. 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. Also, effects of channel bit rate are studied.

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