Review of Dynamic Impairment-Aware Routing and Wavelength Assignment Techniques in All-Optical Wavelength-Routed Networks

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***Abstract*—Since light-paths are the basic connections in wavelength routed networks, their effective establishment is very important. Routing and Wavelength Assignment (RWA) techniques can be divided into two categories. The first category (pure RWA) concentrates on setting up light-paths under the assumption of an ideal physical layer. However, this assumption could be suitable for opaque networks, where a signal is regenerated at each optical switch along its path. On the other hand, as an optical signal propagates along a light-path to its destination in a transparent (all-optical) network, the signal's quality degrades because there is no signal regeneration, thus increasing Bit-Error-Rate (BER) of the signal. However, users would not accept a light-path with a high BER. Even it is not acceptable if the establishment of a light-path causes the BER of other existing light-paths to become unacceptably high. Therefore, considering physical layer impairments, the quality of a light-path must be checked during the light-path setup in the second category. In this article, the operations of dynamic RWA techniques proposed in transparent networks for the second category are reviewed in detail. These techniques are called Quality of Transmission Aware (QoT-aware) RWA and are grouped in two groups: integrated QoT and RWA, and QoT after Pure RWA. Each group can be further divided into direct modelling and indirect modelling sub-groups. A comprehensive discussion is also provided to compare dynamic QoT-aware RWA techniques based on different network and physical layer parameters.**

***Index Terms*—All-optical wavelength routed networks; Dynamic Routing and Wavelength Assignment (RWA), Quality of Transmission-aware (QoT-aware) RWA; Integrated QoT and RWA; QoT after a pure RWA.**

I. INTRODUCTION

ALL-OPTICAL networks are the key technology for supporting huge traffic in future communication networks. To transfer data in a wavelength routed all-optical network, a light-path as the basic mechanism for communication should be established between a source-destination pair by a Routing and Wavelength Assignment (RWA) technique [1]-[4]. A light-path is an all optical communication channel between two nodes in the network that is setup on a path and may span a number of fiber links. This can be done by determining an optical path with an appropriate wavelength between a pair of nodes. Wavelength continuity is the common problem in wavelength routed networks, where the same wavelength must be free along the path on which a connection is going to be setup. This problem can be resolved by using all-optical wavelength converters, where a light-path may use several wavelengths when crossing through different fiber links [2]. Since light-path establishment is the basic and important action to make a connection request between a pair of nodes, its effective establishment is important. If RWA cannot determine a light-path in a proper manner, many future coming connections may be blocked, thus decreasing network throughput.

Many studies on RWA have concentrated on establishing light-paths under the assumption of an ideal physical layer. The ideal assumption could only be suitable for opaque networks, where a signal is regenerated at each optical switch. An RWA technique that considers ideal physical layer is called pure RWA from now on. The blocking of connections in a wavelength-routed network can be reduced by different techniques such as rerouting of established connections [5] and using all-optical wavelength converters in Optical Cross-Connect (OXC) switches e.g., [6]-[7]. As an optical signal propagates along a light-path toward its destination in a transparent wavelength-routed optical network, the signal's quality degrades since there is no conversion to the electronic domain and therefore no signal regeneration. This in turn increases BER of the signal. However, a BER above threshold (e.g. 10^{-3} before FEC) is not acceptable by users. In addition, it is not acceptable if the establishment of a light-path results in increasing the BER of other existing light-paths. Establishing light-paths with lower BER can reduce the number of retransmissions by higher layers, thus increasing network throughput. Therefore, RWA techniques that consider physical layer impairments for the establishment of a light-path, called Quality of Transmission-Aware (QoT-aware) RWA, could be much more practical.

The following RWA surveys can be found in literature. A survey of pure RWA techniques (without considering transmission impairments) can be found in [3]. The work in [8]-[9] has reviewed the techniques (including pre-emption, wavelength management, and routing) that can be utilized for the differentiation of light-paths in the RWA process. The RWA techniques suitable for translucent networks have been reviewed in [10], where a translucent network employs electrical regenerators at intermediate nodes only when it needs to improve the signal quality [10]. A review on the management and control planes required for QoT-aware RWA techniques has been provided in [11]-[15]. The surveys in [11], [16], [17] have provided a review on the static (offline) physical layer impairment-

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aware RWA algorithms in all-optical networks. The surveys presented in [11], [16] have studied in general different topics related to optical networking and physical layer impairments including: DWDM technology, physical layer impairments, optical components, service level agreements, failure recovery, static impairment-aware RWA techniques, impairment-aware control plane techniques, and some dynamic impairment-aware RWA algorithms in both translucent and all-optical networks. However, [11], [16] have not detailed the operation of QoT-aware RWA techniques so that one cannot realize how a specific QoT-aware RWA works. In addition, [16] lacks enough discussions and comparisons on the reviewed techniques.

The motivation of the review in this article is the lack of detailed literature review on the operations of QoT-aware RWA techniques in all-optical networks and their comparisons. The objective in this article is to focus only on all-optical networking and review only the operations of state-of-the-art dynamic QoT-aware RWA techniques in detail. A different point of view and classification (see Sections III, IV, VI) is provided in this article compared with [11], [16]. A comprehensive discussion is also provided to compare QoT-aware RWA techniques based on different network and physical layer parameters in Section VI. Conclusion and future works are stated in Section VII.

II. Network Model

There are two types of RWA problems: static and dynamic. In a static RWA problem [11], [18], a set of fixed connection requests are given and the system should follow two main objectives in establishing these connections [3], [19]: (1) Maximizing the number of connections that can be established if the number of wavelengths is limited (minimizing blocking); and (2) Minimizing the number of wavelengths needed to set up light-paths in order to accommodate the given set of connection requests. In a dynamic RWA problem, a connection request arrives based on a random process with a random holding time. Then, a light-path is established and then disconnected dynamically after finishing the connection holding time. Therefore, RWA decisions should be made rapidly when a connection request arrives at the network. The main objective of a dynamic RWA problem is to find a route and choose a wavelength that maximizes the probability of establishing a connection request. At the same time, RWA should attempt to minimize the blocking probability of future connections. Obviously, it is impossible to keep resource utilization optimal in dynamic RWA [20]. However, light-path setup should be performed by dynamic RWA for some applications such as Internet since IP traffic demand is highly variable [21]. For QoT-aware RWA, besides the aforementioned objectives, both dynamic and static QoT-aware RWA should maintain an acceptable signal quality for light-paths all over the network.

A connection request may be blocked due to three reasons: (1) insufficient resources such as wavelength and wavelength converters (called wavelength blocking); (2) unacceptable BER of the light-path being setup (called quality of transmission blocking), even if there are available network resources to establish the connection request; and (3) unacceptable BER of some of other light-paths already established on the network. The share of the third reason is high in overall blocking [22].

An RWA problem is usually separated into two steps: routing and then wavelength assignment. However, some works make RWA considering both routing and wavelength assignment problems at the same time (i.e., joint RWA). Shortest path, *k*-shortest path, and fixed alternate routing are common routing schemes used in RWA algorithms. For routing, each link has some cost and shortest paths are calculated with respect to these costs. Note that in *k*-shortest path, *k* shortest path routes are used in the routing procedure in RWA. On the other hand, in fixed-alternate routing, there is a set of alternate routes for each pair of network nodes pre-computed offline and orderly stored in a routing table. The actual route for a connection request is selected only from this set. The other issue is the wavelength assignment process, where a suitable wavelength is assigned to the found path in the routing process. The common techniques for wavelength assignment could be First-Fit (FF) [20], random pick [23]-[24], and best-fit [25]-[26]. In the first fit, all of the wavelengths are numbered and when an assignment algorithm seeks for feasible wavelengths on the found route, lower-numbered wavelengths are considered before higher-numbered ones. Then, the first available wavelength is selected. On the other hand, the Random method just searches for all wavelengths available on the found route to determine those which are feasible. Among the feasible wavelengths, one is chosen randomly with uniform probability. In the best-fit method, wavelengths are chosen in such a way that a light-path is routed on the path on which it fits best. In other words, among the wavelengths available for a connection request, a wavelength is assigned to the request that has the least free capacity remaining after accommodating the connection request.

There are two connection signalling methods in wavelength routed networks as centralized or distributed [12]-[13],[16], [27]. In the centralized method, a central network element reachable by all network elements serves the setup of all connections requests. Therefore, the central network element should be aware of the complete network topology, resource availability, and physical parameters through a global database. Using the centralized method, specific sets of light-path requirements such as bandwidth, optical signal quality, and latency can be guaranteed. On the other hand, in a distributed method, each network element is responsible to help for a light-path setup within the transparent domain. Since in a centralized scheme, all the information of a network (such as topology, traffic, and physical layer information) are collected and evaluated altogether in a central entity, it can lead to better performance results than the distributed management. However, the failure of the central unit is a big concern for the centralized scheme. In addition, the centralized management could be suitable for static traffic in which network information rarely changes, and it may not be suitable for dynamic traffic because of the large amount of information that must be managed by a single entity [27]. This clearly leads to the scalability and complexity problems under dynamic traffic. These issues could be the main reasons for the popularity of the distributed signalling. However, the setup latency for distributed networks depends highly on the network topology and signalling control protocols [28]. Unfortunately, most of the articles in QoT-aware RWA have not explicitly determined their connection signalling methods. Therefore, the type of signalling mentioned in this article for a specific QoT-aware RWA is based on the author's understanding from the operation of QoT-aware RWA algorithm. It should be mentioned that a centralized QoT-aware RWA algorithm can be modified to run in a distributed manner, especially those algorithms that compute a specific parameter such as OSNR or BER at the destination node. Therefore, such algorithms are located at the distributed group in this article.

Network dynamics originated from network reconfiguration is an important issue that must be considered in optical networks. These dynamics might be triggered by circuit switching events [29] such as light-path setup, light-path restoration, light-path rerouting, and light-path termination. Transmission power dynamics can be influenced by different components such as EDFAs, automatically tunable attenuators, and spectral power equalizers [29]. In long-haul multi-wavelength optical networks, a chain of EDFAs should be used to compensate for the loss of fiber spans and network components, where the amplifiers normally work in saturated mode. However, in the event of network reconfiguration, the number of WDM signals traversing an amplifier would change fast and the power of surviving channels would increase or decrease due to the cross-saturation effect in the amplifier, thus resulting in fast power transients [4], [30]. Fast power transients can impair the performance of wavelength channels [31], e.g., the dynamics of gain transients in an EDFA can severely affect the BER of an optical signal in receivers [32]. For proper operation of the network, EDFAs should be able to provide broadband variable gain operation, fast transient response to sudden changes in input power, and advanced spectral monitoring and control to adjust to the change of spectral conditions in the network [33].

III. Dynamic QoT-Aware RWA Techniques

In addition to the availability of routes and wavelengths, an RWA technique should also consider transmission impairments. This is called a Quality of Transmission (QoT) aware RWA algorithm. This type of algorithm avoids provisioning a light-path with an unsatisfactory BER. From now on, the term RWA is used for QoT-aware RWA algorithm.

A light-path's QoT is estimated on a route during call setup. Then, if there is a wavelength in the route with an acceptable BER, it is assigned to the light-path. A good RWA algorithm should evaluate the BER of not only a candidate light-path provided by the RWA, but also of any light-path that the candidate light-path might disrupt. This is because a new light-path with an acceptable QoT may provoke so much crosstalk [34] impairment in the network, that QoT for another light-path may drop below the desired threshold.

For a detailed description of the impairments, an interested reader is referred to [11]-[12], [16], [18], [34]-[37]. Physical layer impairments in optical transmission can be divided into three categories according to [36], [38].

1) Linear transmission impairments (related to fiber) such as: Chromatic Dispersion (CD) or Group Velocity Dispersion (GVD), Polarization Mode Dispersion (PMD), and insertion loss that are independent of signal power and affect wavelengths individually. Their effects on an end-to-end light-path can be estimated from link parameters. They depend on the hardware components (e.g., fiber parameters, number of amplifiers) used along the light-path.
2) Non-linear transmission impairments (related to fiber) such as: intra-channel Self Phase Modulation (SPM), Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS), inter-channel crosstalk originated from the nonlinear interaction within fiber spans of several signals co-propagating on different wavelengths such as inter-channel Cross-Phase Modulation (XPM) and inter-channel Four Wave Mixing (FWM) crosstalk between channels [39]. FWM is caused due to the interaction of propagating channels [38], [40]. The non-linear impairments are highly dependent on the allocation of wavelengths on a fiber and decrease OSNR at receivers. The impact of XPM depends on modulation format. For example, modulation of an OOK 10-Gb/s light-path induces changes in fiber refractive index and may harm QPSK modulated 40 Gb/s or 100 Gb/s light-paths existing on neighbor channels [41]-[42]. Notice FWM is typically a problem for WDM systems with low dispersive fibers (e.g., Dispersion-Shifted Fibers (DSF), NonZero-Dispersion-Shifted Fibers (NZDSF)) and at narrow channel spacing [38], [43]. For example, at low data rates such as 2.5Gb/s, the SRS and FWM has been shown to be the dominant impairments on NZDSF transmission channel among all nonlinear effects [44]-[45]. For fibers with a high dispersion as in Standard Single Mode Fiber (SSMF), FWM can be neglected. On the other hand, XPM becomes the main nonlinear impairments in 10-Gb/s NRZ WDM systems operating on SSMF [43]. Recent studies also show that XPM becomes dominant source of nonlinear impairment at 100 Gb/s transmission rate even on NZDSF fiber [46].
3) Other impairments such as: Amplified Spontaneous Emission (ASE) [47] due to amplifiers and intra-channel crosstalk resulted from optical leaks in OXCs due to imperfect demultiplexing that depend on the network status [11], [48]. Note that network status means the current allocation of wavelengths on a given path. There are three types of crosstalk for an OXC switch [2], [34], [49]. The co-wavelength crosstalk is due to the power leak among ports within a central switching module and occurs when multiple light-paths on the same wavelength pass through an OXC switch. The self-crosstalk is imposed by the light-path signal itself. It only happens when multiple light-paths on different wavelengths arrive at same input port and depart from the same output port. The neighbor-port crosstalk is similar to the self-crosstalk with the only difference that source of the neighbor-port crosstalk is not the light-path signal itself, but some other light-paths on the same wavelength.

Of optical transmission quality attributes (such as optical power, optical spectrum, Optical Signal to Noise Ratio (OSNR), Q-factor, Chromatic Dispersion (CD), PMD, and eye diagram), the Q-factor could be the best QoT metric because of its closer correlation with BER. The Q-factor is sensitive to all forms of BER impacting impairments [50]. The Q-factor is directly related to BER by$\mathrm{BER} = 0.5\,\mathrm{erfc}(\mathrm{Q}/\sqrt{2})$, where Q is the value of Q-factor. Since the value of BER in the optical domain is very small, Q-factor is usually used instead of BER. For example, BER of 10^{-9} is equivalent to Q-factor of 6.0. Another metric that sometimes is used in literature is Equivalent Length (EL) [51]-[52]. Equivalent length is an approach to convert a transparent network element located between two adjacent links into an equivalent length of fiber based on its loss/ASE contribution [51]. The EL parameter for a light-path is obtained by linearly combining EL values associated with the network components along the light-path [52]. In other words, equivalent length for a given light-path is the length of optical fiber that would lead to the same signal degradation as the signal degradation along the light-path. Therefore, higher EL for a light-path, the more impairment and lower signal quality for that light-path.

Two major methods have been proposed in literature to obtain information about physical impairments as mathematical modelling and real-time monitoring [12]. The models attempt to capture the most dominant impairments by mathematical formulas. In monitoring, a portion of WDM signal is extracted by tapping optical fibers. Then, Optical Performance Monitoring (OPM) parameters [53] (such as optical power per channel, aggregate optical power, wavelength drift, channel OSNR, and in-band OSNR) can be found in milliseconds [12].

Many researchers have used the modelling approaches to approximate a physical impairment, e.g., the interaction of CD and SPM impacts on BER or Q-factor [54]-[55]. When some impairment cannot be modelled, it can be considered with the worst-case margins, e.g., [56]-[58]. Some meta-heuristic algorithms such as Genetic [39] and Ant Colony Optimization [59] have also been suggested to obtain better performances, but they have extra complexity and may need more time than heuristic algorithms to set up a suitable light-path. So far few works have included wavelength conversion on the modelling of QoT-aware RWA. Therefore, when modelling of impairments, most of the works studied in this article assume OXC nodes without all-optical wavelength conversion possibility. Since all-optical networking is considered in this paper, the converters in this domain must be all-optical wavelength converters.

Fig. 1 shows the classification of RWA techniques, where the dynamic QoT-aware RWA techniques can be divided into two major categories:

1) **Integrated QoT and RWA:** Impairments are modelled as a cost function on connection links and then RWA is solved. Then, a routing algorithm finds a light-path with minimum impairments. After determining and establishing a light-path, some techniques may verify the quality of the light-path in order to make sure that its QoT is satisfied.
2) **QoT after a Pure RWA:** A pure RWA is first solved without considering QoT and a number of candidate light-paths are found. Then, the QoT criteria are applied on the candidate light-paths in order to find the light-path that satisfies the desired QoT parameters.

When impairment is directly modelled in the RWA process, it is called direct modelling (see Fig. 1). On the other hand in indirect modelling, another network parameter which is indirectly relevant to impairment is used in the RWA process, and finally an impairment model may be applied on the chosen light-path in order to validate it. For example, ASE is directly dependent on physical length and intra-channel crosstalk is directly dependent on the number switches a light-path passes through them. For each specific modelling, one can find either centralized or distributed management schemes as depicted in Fig. 1. The last level for classifying dynamic QoT-aware RWA techniques is the QoT metric they use for accepting or rejecting a light-path, shown for only one item in Fig. 1 to avoid chaos.

In the following sections, the operation of each dynamic QoT-aware RWA technique is studied. For each technique, the QoT metric used for evaluation of light-paths for admission is also stated. For the remainder of this article, Table I shows general notations.

TABLE I
GENERAL NOTATIONS

AGC	Automatic Gain Control
ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
CD	Chromatic Dispersion
DCF	Dispersion Compensation Fiber
DRA	Distributed Raman-Amplifiers
EDFA	Erbium-Doped Fiber Amplifier
EL	Equivalent Length
FC	Filter Concatenation
FF	First Fit
FWM	Four Wave Mixing
GA	Genetic-based Algorithm
ISI	Inter Symbol Interference
MPI	Multi-Path Interference
NRZ	Non-Return-to-Zero
NZDSF	Non-Zero Dispersion Shifted Fiber
ODB	Optical DuoBinary
OOK	On-Off Keying
OSNR	Optical Signal to Noise Ratio
OXC	Optical Cross-Connect
PMD	Polarization Mode Dispersion
QoT	Quality of Transmission
QPSK	Quadrature Phase Shift Keying
RD	Residual Dispersion
RWA	Routing and Wavelength Assignment
RZDQPSK	Return Zero Differential Quadrature Phase Shift Keying
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
SSMF	Standard Single Mode Fiber
XPM	Cross-Phase Modulation

IV. INTEGRATED QOT AND RWA

In this category, impairments are mapped to the cost of links and then RWA is solved. Higher cost value for a link shows more severe degradation due to a particular impairment as signal is transmitted through the link, whereas a lower cost implies that this link is more secure for signal transmission [18]. Since in realistic networks, nonlinear impairments are all dependent on real-time traffic load and power conditions [50], link costs must also consider the network traffic conditions. Different metrics can be used to model the cost of links in QoT-aware RWA algorithms such as: link length [59], [75], [79]-[80], [82], hop count [82], congestion [75], PMD [18], CD [18], Q-factor [50], [60], [64], [82], noise [75], noise variances [23], and FWM [83].

Now, the RWA techniques that are integrated with the QoT problem are reviewed. Table II displays a summary of the

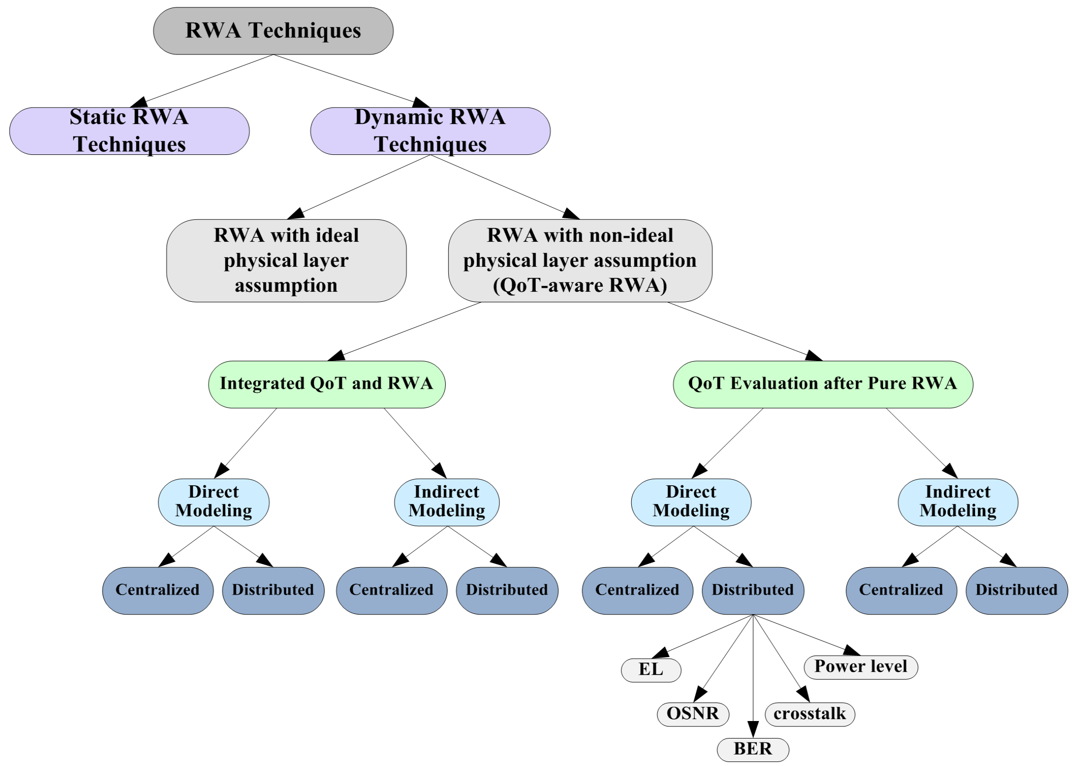

Fig. 1. Classification of QoT-aware RWA Techniques (the QoT metric evaluation classification displayed at the last line is true for all centralized/distributed items)

TABLE II
THE INTEGRATED QOT AND RWA TECHNIQUES

	Operation	QoT metric	Ref. #	Model Ref.#	Evaluated Impairments	Link Cost Function	Routing	Wavelength Assignment	Modulation/Bit rate/ Channel spacing
Direct Modelling of Impairments	Centralized	Q-factor	[60]	[61]-[63]	ASE, XPM,FWM, SPM, intra-channel crosstalk	Q-factor penalty based on ASE, XPM, FWM, crosstalk, SPM	k-shortest paths	Chosen from a sorted list	NRZ-OOK 10 Gb/s, 50 GHz
			[64]	[65]	PMD, ASE, CD Filter concatenation effects, intra-channel crosstalk	Q-factor	k shortest paths	N/A	N/A
			[66]-[67]	[68]	Q-factor based on electrical noise variances of XPM, FWM, switch crosstalk, ASE	Availability of each wavelength, gain/loss of each wavelength, electrical noise variances of signals 1 and 0 of each wavelength, propagation delay	Non-dominated routes	Most used	NRZ-OOK, 10 Gb/s
		BER	[69]-[70]	[36], [60], [62]-[63]	ASE noise, the combined effects of SPM/GVD and optical filtering, FWM, and XPM	Q-factor penalty based on ASE, FWM, XPM, SPM/GVD	k-shortest path	FF	10 Gb/s, 50 GHz
	Distributed	BER	[23]	[24]	ASE, intra-channel crosstalk, FWM, XPM	Summation of the noise variances	shortest path	FF, Random Pick	NRZ-OOK, 10 Gb/s, 25 GHz
			[50]	[4]	Q-factor monitoring components used at the inputs of every OXC	average Q-factor degradation in decibel of current light-paths established on a link	shortest path	FF	Mixed 2.5, 10, 40 Gb/s
		OSNR	[71]-[74]	OSNR analysis due to ASE noise [4]	OSNR due to accumulated ASE	Residual dispersion	shortest path	N/A	NRZ-OOK, ODB, Mixed 10, 40 Gb/s light-paths , 100 GHz
Indirect Modelling of Impairments	Centralized	Q-factor	[75]	[76]	Q-factor based on FWM, XPM, and OSNR based on gain saturation	length of the path congestion of the path noise	Bellman Ford shortest path	Best Fit	10 Gb/s, 50 GHz
		N/A	[77]	No model	N/A	link length, wavelength availability on the link, number of light-paths crossing at the end nodes of the link	shortest path	N/A	N/A
	Distributed	OSNR	[78]-[81]	[79]	OSNR based on ASE noise, Gain saturation, intra-channel crosstalk, PMD, and FWM	link length, link availability	shortest path	FF	OOK 40 Gb/s, 100 GHz

RWA techniques along with the impairment model, evaluated impairment parameters, cost function, routing, wavelength assignment methods, and information about modulation/ bit rate/ channel spacing. Many techniques in this category directly integrate the modelling of impairments in the RWA process. However, to reduce the computation time, there are techniques described in [75],[79] that incorporate network parameters such as congestion, link length and link availability in RWA. This is because of their correlation with physical impairments. When the wavelength assignment method has not been stated for a technique, it is shown with N/A in Table II.

A. Direct Modelling of Impairments

Under the integrated QoT and RWA category, one can find the following centralized and distributed schemes for the direct modelling of impairments.

1) Centralized techniques: In the following, the RWA techniques are studied based on the metric used for QoT evaluation.

a) QoT Evaluation with Q-factor: The research in [60] is a centralized scheme in which all the information of network (such as topology, amplifiers, fiber characteristics, attenuation of each span, etc.) and traffic demands (such as number of connection requests, their source-destination) are first collected. A Q-factor penalty metric is then computed for each link based on the variances of ASE, XPM, FWM, intra-channel crosstalk, and SPM impairments. The penalty factor is then assigned as a cost parameter to the link, reflecting the corresponding degradation on the signal quality on that link. For a connection request between any source-destination pair, k-shortest paths are considered in RWA. The k-shortest paths can be found using the algorithm stated in [84]. Among them, the path that includes a wavelength with the best Q-factor (including the effects of XT, ASE, XPM, FWM, and SPM) is chosen, while considering already established light-paths. To improve the computational efficiency, all the wavelengths can be first ordered based on their Q-factors on each link. After determining a path for a connection, a wavelength can be chosen from the ordered list. The transmission architecture in [60] includes a double stage EDFA at the end of each SMF span. In addition, there is a DCF fiber module at the intermediate stage of the EDFAs for appropriate dispersion management. At the beginning and end of any transmission link, respectively, there are pre-compensating and post-dispersion compensation fiber modules.

In [64], impairments such as PMD, ASE, and CD are modelled for RWA. First, all the information relevant to network characteristics (such as fiber characteristics, topology, link capacity) and traffic demands (e.g., number of demands, end nodes) are collected. A Q-factor that includes the impairments is computed for each link as a cost. This factor is based on eye penalty and noise penalty. The eye penalty is due to the effects of CD, PMD, and filter concatenation. On the other hand, the noise penalty is due to ASE and intra-channel crosstalk. In RWA, the k shortest path technique is considered to find a number of candidate light-path as for each connection request. Then, the quality of each light-path for a connection request is evaluated to be acceptable. For a light-path with unacceptable signal quality requirements, its relevant route is removed from the k shortest paths and the RWA process is repeated again. Although [64] has evaluated this technique for static traffic, it can be used for dynamic traffic as well.

In the multi-cost RWA algorithm [66]-[67], 1+4m parameters are assigned to each link, where m is the number of wavelengths in the network. These parameters for a given link include propagation delay of the link and four parameters for each individual wavelength λ on the link as gain/loss on λ, electrical noise variance of the signal transmitted for bit "1" on λ, electrical noise variance of the signal transmitted for bit "0" on λ, and availability of λ. Clearly, these parameters depend on the state of the network. These link-related parameters are added over a given path to obtain a set of path-related parameters. For a given path, a Q-factor is computed for each wavelength on the path. Then, the Q-factor of available wavelengths on the path is tested to be more than a given threshold. If the Q-factors of all wavelengths are not acceptable, the given path is not an acceptable path. To compute Q-factor, electrical noise variances due to ASE, switch cross-talk, XPM and FWM are used to compute electrical noise variances of signal 1 and signal 0. In [66]-[67], path domination is defined as follows. Path p_1 can dominate path p_2 if propagation delay of p_1, Q-factor of p_1, and the number of available wavelength of p_1 are all better than the same parameters in path p_2. To set up a light-path between node s and node d, the multi-cost RWA algorithm first finds the set of non-dominated light-paths between them. Then, three optimization functions can be applied to the cost vectors of these light-paths in order to find the optimum light-path. The Most Used Wavelength (MUW) chooses the light-path whose wavelength is most used among established light-paths. The Better Q performance (bQ) selects the light-path with the highest Q-factor. In the Mixed better Q and wavelength utilization (bQ-MUW), among the light-paths with Q-factor close to the highest Q-factor, the light-path with most used wavelength is picked. After establishing a light-path, if the Q-factor of some existing established light-paths falls beneath a given threshold, they are all rerouted in order to achieve acceptable Q-factors. It is shown that better performance results in terms of blocking and number of re-routings can be obtained by bQ-MUW.

b) QoT Evaluation with BER: The ICBR-Diff [69]-[70] supports differentiation of services so that various BER thresholds are considered for accepting/blocking connection requests. Notice connection requests belong to a number of classes with different BER requirements. In routing phase for a connection request, the Q-penalty (computed based on ASE, FWM, XPM, and SPM/GVD) is considered as cost of links in the network. If all wavelengths on a particular link are occupied, its cost is set to infinity. After assigning link costs, up to k alternative routes are computed by using the Dijkstra algorithm for each connection request. If there is at least one common wavelength available on every link of a route, that route with the chosen wavelength is considered a candidate light-path. Then, the BER of each candidate light-path is calculated against the signal quality requirement of the connection request (depending on the class of request). Next, the candidate light-path with the highest acceptable BER (i.e., closest acceptable BER) is assigned to the connection request. This is unlike the impairment-aware best-path schemes, e.g., [40], that choose the candidate light-path with the smallest BER (i.e., the best light-path). By this mechanism, more admission opportunity can be provided for future coming connection requests. In these works, each network link consists of a sequence of SMF spans, followed by EDFAs and in line DCF.

2) Distributed techniques: In the following, the RWA techniques are studied based on the metric they use for QoT evaluation.

a) QoT Evaluation with BER: In the adaptive QoT-aware RWA proposed in [23], the cost of each link is adaptively set to constant value α plus the summation of the following noise variances: ASE, intra-channel crosstalk, and nonlinear inter-channel FWM/XPM crosstalk. Then, the Dijkstra shortest path algorithm is used to find the least cost path. Since noise variances are additive hop by hop, the total noise variance could be a better choice than the Q factor to represent the cost in any shortest path algorithm. Clearly, using this cost function, the best route based on physical impairments can be found. When network is idle or lightly loaded, the effect of physical impairments are likely negligible. In this case, the costs of links are reduced to constant value α and routing becomes equivalent to shortest hop routing. After establishing a light-path, the BER for light-paths that share one or more nodes with the setup light-path are re-estimated to account for crosstalk and nonlinear components that are injected or removed. If BER is not acceptable for an existing light-path, the process of finding a new light-path is started.

In [50], Q-factor monitoring components are used at the input ports of each OXC switch. Many Q-monitoring components should be used in the network in order to obtain more up-to-date network conditions and better accuracy in a path Q-factor computation. Two algorithms have been proposed in [50], namely Q Measurement (QM) and Adaptive QoS (AQoS). In QM, each link is assigned a cost value equivalent to average monitored Q-factor degradation in decibel of current light-paths established on the link. When a connection request arrives, a standard shortest path algorithm is used to find the route with the least path Q-factor degradation. Alternate routes can also be found (called ALT-QM), and then sorted in order to obtain the best-Q-route, the second best-Q-route, and so on. Note that there is a close correlation between the linear sum of link Q-factor degradations and the end-to-end path Q-factor degradation. This technique does not estimate the Q-factor by incorporating the new light-path into the network. Instead, it uses available Q-factor measurements from existing established light-paths to find a route, in the hope that what currently performs the best will still perform the best after the establishment of the new light-path. However, this hope may fail in practice. In addition, the established light-path may not satisfy the required BER performance or even may degrade the BER of other established light-paths to an unacceptable level. Therefore, an admission control mechanism is used after RWA to estimate BER mathematically in order to accept or reject a given light-path. In AQoS, each source node keeps track of the number of blocked local calls due to BER constraint (N_{BER}) and number of blocked local calls due to lack of wavelengths (N_w). Once a call arrives in a source node, it checks two conditions. If $N_{BER} \geq N_w$, then the source picks the route that results in the smallest Q-degradation. Otherwise, the route with most available idle path wavelengths from the sorted list of best-Q route, the second best-Q route, etc. is chosen so that the selected route satisfies both wavelength and BER constraints. It is shown that AQoS not only can provide light-paths with good BER, but also can efficiently utilize wavelengths. Notice [50] uses amplifier-free OXCs , and EDFAs with AGC uniformly placed on transmission links to avoid gain changes in EDFAs. Moreover, light-paths have different bit rates as 2.5, 10, and 40 Gb/s.

b) QoT Evaluation with OSNR: A chromatic dispersion-based RWA technique has been suggested in [71]-[74], where optical Tunable Dispersion Compensating (TDC) devices are used on transmission links. Over 10 Gb/s transmission channels, connections with different modulations (Non-Return-to-Zero (NRZ) and Optical DuoBinary (ODB)), bit rates (10 and 43 Gb/s), and TDC devices (with and without) are supported. Notice no electrical equalization is used at receivers. For dispersion management, each fiber span on a transmission link includes the following modules in sequence: a DCF module, an EDFA, a transmission fiber, an EDFA, and a DCF module. Since edge wavelengths usually have higher Residual Dispersion (RD) than wavelengths located close to zero-dispersion wavelength due to imperfect dispersion compensation, residual dispersion should be evaluated instead of CD. This technique integrates CD information in both routing and wavelength assignment sub-problems. The link cost between any pair of nodes is defined based on the distance between them and the average RD of all available wavelengths. This increases the probability of finding a path with the lowest total accumulated RD. After finding a path, this technique finds a wavelength that has the highest tolerable amount of accumulated RD among all available wavelengths. After finding a light-path, its OSNR is computed from the accumulated ASE noise along the light-path. The light-path is setup if its OSNR is greater than a given threshold value. Otherwise, system attempts to find another light-path.

It should be noted that using electrical equalization at receivers, the effects of linear impairments can be relieved and a high tolerance can be provided to PMD and CD, and therefore, RD evaluation will be irrelevant. Using coherent receivers for the detection of POLarization-MUltiplexed (POLMUX), Quadrature Phase Shift Keying (QPSK) optical signals can reduce the symbol rate, and therefore, the dispersion tolerance can be improved, e.g., 111 Gb/s POLMUX-RZ-DQPSK [85] and 43 Gb/s POLMUX-QPSK [86]-[87] using coherent detection and electronic equalization.

B. Indirect Modelling of Impairments

The following centralized and distributed schemes can be found for indirect modelling of impairments within routing under the integrated QoT and RWA category:

1) Centralized Techniques: In the following, the RWA techniques are reviewed based on the metric used for QoT evaluation.

a) QoT Evaluation with Q-factor: In [75], the RWA is based on a generalized cost function, where the cost function could be either the length of the path (as the standard shortest path), or the congestion of the path (i.e., the standard deviation of the occupancy of a link), or the noise of the channel on the path. Based on these cost parameters, three different RWA algorithms have been proposed based on the Bellman Ford [88] shortest path. Using congestion as a cost, RWA indirectly seeks for a path with smaller nonlinearities as well because highly loaded paths produce higher nonlinear impairments. This cost can also lead to balance traffic load in the network. Using noise as a cost, RWA seeks for the best path with the smallest noise. During RWA procedure, a number of candidate light-paths may be found. At the end of each RWA, the Q-factor is computed for each candidate light-path, using the analytical models presented in [76], based on FWM, XPM, and OSNR according to gain saturation. A candidate light-path is rejected if its Q-factor is less than a given threshold Q_A. Otherwise, the system probes the network with the candidate light-path and computes the Q-factor of all affected existing connections. If the Q-factor of an existing light-path becomes smaller than a given threshold Q_B, that candidate light-path is dropped. The procedure is repeated until either a suitable light-path is found or the connection request is blocked. Each fiber span in [75] includes in sequence a 40km SMF, a 8km DCF, and an EDFA.

b) No QoT Evaluation: A QoT-aware RWA scheme called Shortest Path Adaptive Link Weights (SPALW) has been presented in [77]. The cost of a link in this technique is a weighted function based on three parameters as:

1) physical link length to account for ASE noise
2) wavelength availability factor on the link equal to the number of used wavelengths divided by the number of unused wavelengths. This leads to establish light-paths through the links with more available wavelengths when using shortest path routing techniques. This can increase the chance of satisfying wavelength continuity constraint.
3) sum of the number of light-paths crossing at both the head and tail nodes of the link. This summation accounts for the intra-channel crosstalk so that when the summation is a small amount there is a small intra-channel crosstalk on the nodes and vice versa. After assigning cost for each link, the shortest path algorithm is used to choose a path with the minimum cost.

2) Distributed Techniques: In the following, the RWA techniques are reviewed based on the metric they use to evaluate QoT.

a) QoT Evaluation with OSNR: An adaptive cost function based on simple network parameters such as link length and link availability is used for network links in the routing problem [78]-[81]. These parameters are related to network impairments because link length, link availability, and the number of hops have high correlation with the noise accumulated along a light-path. By increasing link length, higher gains must be provided by optical amplifiers to compensate for losses, thus increasing ASE along the path. In addition, a light-path established through a long-hop path encounters a higher intra-channel crosstalk noise than a low-hop path. Furthermore, the amplifier gain and noise depend on the total input signal power of an optical amplifier. Therefore, link usage has impact on amplifier saturation and ASE noise generation. Upon a call request arrival, a wavelength is selected using the First-Fit technique. Then, considering the cost function a routing algorithm is used to find a suitable light-path with the lowest cost. Finally, pulse broadening due to PMD and OSNR (based on ASE noise generation, ASE saturation, intra-channel crosstalk, and amplifier gain) of the selected light-path are evaluated at the destination to be more than given pulse broadening and OSNR thresholds, respectively. When the quality of the light-path is not acceptable, a new light-path is tried to be found. In order to neglect the FWM effect, moderate laser powers (maximum of 0 dBm) and non-zero dispersion shifted fibers (NZDSF) with chromatic dispersion coefficient between 1 and 6 ps/nm×km at 1550 nm can be used in the network [4], [78]. Among NZDSF fibers, large effective area Corning LEAF fiber and Lucent TrueWave XL fiber are more suitable to compensate FWM [4], [89]. They allow higher levels of power to be sent through the fiber than standard NZ-DSFs, minimizing FWM effects. Notice the OXC switch architecture is the same as in [90].

V. QoT Evaluation after Pure RWA

All techniques studied in this section have two steps. First, a light-path is computed using a certain RWA policy that does not consider any effect of physical impairments. Then, the QoT of the light-path is estimated at the second step. Many techniques in this category directly integrate the modelling of impairments in RWA. However, an indirect technique such as [34] counts the number of intra-channel crosstalk components to pick a wavelength to reduce the computation time. Table III and Table IV summarize the techniques in this category, where N/A refers to an unexpressed wavelength assignment method.

A. Direct Modelling of Impairments

Under the QoT evaluation after pure RWA category, a number of centralized and distributed schemes have been proposed for direct modelling of impairments as follows.

1) Centralized techniques: Here, the RWA techniques are reviewed based on the metric they use for QoT evaluation.

a) QoT Evaluation with Q-factor: In [91]-[94], fairness is considered in RWA in a network with a centralized management, where minimizing blocking probability and BER, and maximizing blocking probability fairness and BER fairness are main objectives. Each fiber span consists of SMF, an EDFA with AGC, and a dispersion compensation device. To compute Q-factor, Inter Symbol Interference (ISI), ASE noise, inter-channel crosstalk and intra-channel crosstalk variances are accounted. Once a call arrives, all wavelengths are reviewed in turn in order to obtain a number of shortest paths for the requested call. Each shortest path on a wavelength that satisfies Q-factor both for all previously established calls and for the tentative call is marked as a usable light-path. Then, to pick an appropriate light-path among the usable light-paths, three

TABLE III
THE QoT EVALUATION AFTER RWA: DIRECT MODELLING OF IMPAIRMENTS

	QoT metric	Ref.#	Model Ref#	Evaluated Impairments	Routing	Wavelength Assignment	Modulation/Bit rate/ channel spacing
Centralized	Q-factor	[91]-[94]	[95]	ISI, ASE, intra-channel and inter-channel crosstalk	Shortest-path	FF	NRZ-OOK, 10 Gb/s, 25 GHz
	N/A	[39]	[4]	PMD , ASE noise	A GA algorithm finds the best route and wavelength		10 Gb/s
	BER	[28], [96]	[4]	insertion loss, incoherent crosstalk, and noise (including ASE noise, shot noise, and thermal noise)	Shortest-path	FF on offline ordered wavelengths	NRZ-OOK, 10 Gb/s, 50 GHz
		[97]	[38], [98]	PMD, nonlinear effects, intra-channel crosstalk	Least congested	N/A	40 Gb/s, 100 GHz
		[99]	[100]	ASE noise, Residual Chromatic Dispersion	minimum cost flow	Joint RWA	ODB, RZDQPSK 40 Gb/s, 100 GHz
	OSNR	[25]	[25]	OSNR due to ASE noise accumulation, accumulated PMD, CD, and XPM	Shortest-hop	Joint RWA	10 Gb/s
		[101]	[25]	OSNR based on ASE, PMD, CD, SPM, XPM	Shortest-hop	Joint RWA	10 Gb/s
		[22]	[34]	ASE noise; co-wavelength, self-wavelength and neighbour crosstalk of OXCs, and attenuation	Shortest-path	FF, Random	N/A
Distributed	BER	[24]	[24]	powers, ASE noise, intra-channel crosstalk	Shortest-path	FF	NRZ-OOK, 1 Gb/s, 100 GHz
		[102]	[103] for noise figure and [4] for BER	amplifier noise accumulation, amplifier gain saturation, wavelength dependent gain, loss along light-paths	Shortest-path	FF	N/A
		[40]	[104]	FWM	Shortest-path	N/A	OOK, 50, 100, 200 GHz
		[48]	[4]	ISI, ASE noise, inter-channel crosstalk, intra-channel crosstalk	alternate	FF	NRZ-OOK, 10 Gb/s, 25 GHz
		[105]	[24]	Intra-channel crosstalk and ASE noise	Shortest-path	FF, Random, Shortest distance	NRZ-OOK, 1 Gb/s
		[106]	[90]	OSNR(intra-channel crosstalk and EDFA ASE noise, and Raman-amplifier noise including ASE noise and MPI)	Shortest-path	FF	2.5 Gb/s
		[107]	[24]	ASE, shot noise, thermal noise, crosstalk caused by SRS, the inter-channel and intra-channel crosstalk	Fixed Shortest-path	FF, Random	NRZ-OOK, 1 Gb/s, 100GHz
	Power level	[108]	[109]	optical power level based on ASE	*k*-shortest path	FF	2.5 Gb/s
		[21]	[110]	optical power level based on ASE	fixed alternate	N/A	N/A
		[59], [111]	[109]	Optical power level based on ASE	*k* Shortest-path	FF	10 Gb/s
	OSNR	[112]-[113]	[90]	OSNR(intra-channel crosstalk and EDFA ASE noise, and Raman-amplifier noise including ASE noise and MPI), PMD	Shortest-path	FF	10 Gb/s, 100 GHz
		[114]	[90]	OSNR(intra-channel crosstalk and EDFA ASE noise, and Raman-amplifier noise including ASE noise and MPI), PMD	*k* Shortest-path	FF, last-fit chosen from ordered list	10 Gb/s, 100 GHz
		[90], [115]-[116]	[90]	OSNR(intra-channel crosstalk and EDFA ASE noise, and Raman-amplifier noise including ASE noise and MPI), PMD	Shortest-path	FF	10, 20, 40 Gb/s, 100 GHz
	OSNR , EL	[52], [117]	[1]	ASE, PMD, and CD	Shortest-path	FF	NRZ-OOK, 10 Gb/s
	EL	[118]	N/A	ASE, PMD, CD, SPM	Shortest-hop	FF	N/A
	Crosstalk	[119]	[4]	ASE, intra-channel crosstalk	Shortest-path	FF, Random, wavelength with best BER, worst BER	NRZ-OOK, 10 Gb/s
		[120]	[121]	penalty based on intra-channel crosstalk and adjacent port crosstalk, attenuations, and variance due to XPM and FWM	Fixed Shortest-path	Chosen from ordered list	NRZ-OOK, 10 Gb/s, 100 GHz
	Q-factor	[122]	[68]	attenuation, CD, ASE, XPM, FWM	Shortest-path	FF	10 Gb/s, 50 GHz

TABLE IV
THE QoT EVALUATION AFTER RWA: INDIRECT MODELLING OF IMPAIRMENTS

Operation	QoT metric	Ref.#	Model Ref#	Evaluated Impairments	Routing	Wavelength Assignment	Modulation/Bit rate/ channel spacing
Centralized	crosstalk	[34]	[4]	weighted counts of the number of intra-channel crosstalk components	Fixed Shortest-path	Random, FF, Most Used, Least Used	NRZ-OOK, 10 Gb/s
Distributed	crosstalk	[123]-[124]	N/A	penalty factor based on intra-channel crosstalk and adjacent port crosstalk power level attenuations	Fixed Shortest-path	Chosen from ordered list	NRZ-OOK, 10 Gb/s, 100 GHz
		[77]	N/A	counts of the number of intra-channel crosstalk components	Shortest-path	N/A	N/A

techniques have been suggested: (1) choose the light-path with the shortest path; (2) choose the light-path with the highest Q-factor (equivalent to lowest BER) by which the insertion of new inter-channel and intra-channel crosstalk is relieved when setting up the light-path. Compared with the shortest-hop technique, however, a long-hop light-path may be established; and (3) choose the light-path that maximizes (among all possible wavelengths) the minimum Q-factor (among all paths crossed by the tentative light-path and itself). These algorithms try to minimize BER (maximize QoS) in network. On the other hand, the third technique is fairer than the first and second algorithms studied in [91]-[92].

b) No QoT Evaluation: A Genetic-based Algorithm (GA) with a centralized management has been presented in [39], where there are two constraints as PMD constraint and ASE impairments constraint. There is also one fitness function that must be optimized during RWA. Note that network nodes and links are respectively equipped with all-optical wavelength converters and amplifiers. The procedure for fitness computation in GA takes into account different variables involved in RWA with the objective of setting up the highest number of light-paths in an optimized form. The GA algorithm computes its fitness function for light-path i on wavelength k as the weighted sum of individual costs due to the number of wavelength converters, number of cascaded amplifiers, number of PMD compensators, path length, number of links of light-path i that are currently using wavelength k, and number of idle wavelengths referring to path i, in which wavelength k is not used. The GA tries to find the best light-path with two additional constraints such as minimizing number of used wavelength converters and cascaded amplifiers, thus enhancing the optical signal quality.

c) QoT Evaluation with BER: The work in [28], [96] has proposed a centralized RWA technique that considers both BER and latency constraints at the same time. In this technique, connection requests are saved in a First Come First Served buffer and then setup in sequence. This technique uses fixed routing algorithm (shortest path and alternate path with one main and one alternate path) for routing, and offline wavelength ordering for wavelength assignment. Using wavelength ordering, the wavelength considered for a light-path setup would find a small number of adjacent-port crosstalk terms in OXCs. In the wavelength assignment process, a wavelength is picked from the ordered list like the First-fit technique. The impairments considered in this technique are insertion loss, incoherent crosstalk, and noise (including ASE noise, shot noise, and thermal noise at receivers). As soon a light-path satisfies BER requirements, it is accepted. BER is estimated similar to [24], [107]. When a light-path is established, the BER for light-paths that share one or more OXCs with the new light-path are re-estimated. A timeout mechanism, which depends on the delay-sensitive application, has also been considered for the setup latency of connection requests. If a connection cannot be setup within T_{max} units of time, it will be blocked. In physical infrastructure, EDFAs with AGC are utilized on transmission links. In addition, OXCs use EDFAs inside as in [90].

A dynamic resource allocation technique that considers signal transmission impairments with differentiated service classification has been presented in [97]. Fiber attenuation and dispersion are compensated by EDFAs and dispersion compensation devices. Optical switches are equipped with all-optical limited-range wavelength converters. The link weight from node i to node j is set to $1+\delta\times\alpha_{ij}$, where δ is a constant value and α_{ij} shows the number of occupied wavelengths on the link. If all wavelengths are occupied, the link weight is set to infinity. Moreover, a subset of wavelengths is dedicated to the connection requests with priority r. In addition, a BER threshold $D(r)$ is defined given for class r. A total combinational cost function is also defined for a light-path based on BER due to PMD on the light-path links, BER due to nonlinear effects during transmission on the light-path links, BER due to intra-channel crosstalk accumulation in the OXCs along the light-path, and the number of all-optical wavelength conversions required for establishing the light-path. Once a connection request with priority r arrives, least congested routing (i.e., the routes with more available wavelengths considering the link weights) is employed to find candidate light-paths on the wavelengths allocated for priority r, where the constraint of limited range wavelength conversion is taken into consideration during the wavelengths assignment procedure. Among the candidate light-paths, the light-path LP that satisfies all the following conditions is accepted for setup: (1) total cost of LP is smaller than a BER threshold given for class r ; (2) BER due to intra-channel crosstalk accumulation on LP is smaller than $D(r)$; (3) BER due to PMD on LP is smaller than $D(r)$; and (4) BER due to nonlinear effects on LP is smaller than $D(r)$. Otherwise, if no such a condition satisfies for any candidate light-path, the connection request is blocked. Note transmission impairments caused by PMD and nonlinear effects are calculated link by link, and the impairment caused by crosstalk accumulation is computed throughout the entire network.

In [99], accumulated CD and ASE noise are considered in light-path setup procedure. In addition, this work considers 40 Gb/s bit rate using Return Zero Differential Quadrature Phase Shift Keying (RZDQPSK) and Optical Duo-Binary (ODB) modulation formats with Forward Error Correction (FEC). Furthermore, Non-Zero Dispersion-Shifted Fiber (NZDSF) and SSMF fibers are used on different transmission links along with EDFA. Moreover, OXCs use EDFAs both at inputs side and output side of the switch as in [90]. In each fiber span, DCF is placed before the transmission fiber to achieve the desired compensation. Notice the 40 Gb/s signal is strongly affected from the uncompensated CD which causes pulse spreading in time. Although CD is compensated by placing DCFs to some extent, however, the compensation is not the same for every wavelength. This is why accumulated residual CD is considered in this work. The BER threshold (BER_{TH}) and CD threshold (CD_{TH}) are defined to check the acceptability of a light-path. This work jointly considers path computation and wavelength assignment using a layered graph, in which only available wavelengths are represented in the graph. The capacity of one is assigned to every available wavelength in order to treat layered graph as a flow network. By this mechanism, it is possible to calculate the maximum number of wavelength disjoint paths which represents the maximum flow between a pair of nodes in the network. Moreover, the cost of each link is set to its physical length so that the maximum flow at the minimum cost can be calculated, which represents the maximum number of disjoint paths with minimum total length. By finding the maximum flow at the minimum cost, the maximal set of wavelength disjoint paths with the minimum total length is found (as candidate light-paths) from source to destination of a connection request. Among the candidate light-paths with accumulated CD less than CD_{TH} and BER less than BER_{TH}, each candidate light-path LP is assigned a cost proportional to hops number of LP divided by residual dispersion of LP. Finally, the candidate light-path with the smallest cost is selected for the setup process.

d) QoT Evaluation with OSNR: In [25], homogeneous physical infrastructure is utilized with the same fiber type on all links and 10 Gb/s traffic streams. Non-Zero DSF fibers and EDFAs are also used on transmission links. Three OSNR parameters are approximated for each path as OSNR_{ASE} due to ASE noise accumulation, $\text{OSNR}_{PMD,CD}$ due to accumulated PMD and CD (as linear impairments), and OSNR_{XPM} due to XPM (as a nonlinear impairment). Clearly, $\text{OSNR}_{PMD,CD}$ can be neglected when using CD compensation modules and when the overall PMD with respect to bit duration is small. The third term depends on dynamic configuration of the network since it varies with wavelength allocation on each fiber. The reason for considering only XPM as nonlinear impairment in [25] is that XPM is typically the main limiting factor in

WDM systems with high data rate, especially when using non-zero dispersion fiber (NZDF) and NZDSF fiber [46], [125]-[126], as discussed in Section III. To evaluate OSNR$_{XPM}$ penalty, it is assumed that this penalty is monotone increasing function with number of used wavelengths per fiber and power per wavelength channel, and is monotone decreasing function with increasing channel spacing and dispersion. To compute OSNR due to XPM, an empirical function (as a look-up-table) is obtained by Mont-Carlo simulation on a defined test link based on the knowledge of fiber characteristics, number of wavelengths in use, length of the fiber span, and transmitted power. The OSNR$_{XPM}$ penalty depends on the dynamic configuration of the network since it varies with the number of wavelengths allocated on each fiber and with their spectral assignments. Once a connection request arrives, RWA is solved and a number of candidate light-paths are found if their OSNR (obtained from $OSNR_{ASE}$ - $OSNR_{PMD,CD}$- $OSNR_{XPM}$) are higher than a given threshold. Then, the candidate light-path with the highest OSNR is accepted.

In [101], the best OSNR technique is used in which after finding a candidate light-path by a joint RWA scheme, its OSNR is computed based on ASE, PMD, CD, SPM and XPM. Then, among all candidate light-paths, one with the maximum OSNR is picked for setup. This technique may have high setup latency because all possible candidate light-paths must be examined before establishing a light-path with the best OSNR. The work in [101] is similar to [25], except that SPM has not been evaluated in [25]. Non-Zero DSF fiber and EDFA are also used in each fiber span on transmission links.

A Crosstalk Interference Avoidance (CIA) algorithm has been proposed in [22] to minimize the blocking probability due to inappropriate OSNR for some of the light-paths already active in the network. Under CIA, it is avoided to use the wavelengths that would degrade the fragile light-paths in terms of OSNR. When a new connection request arrives, based on the wavelength occupation table of the network and the list of setup light-paths, the control plane first finds already established light-paths (called LPIs) that would be degraded in terms of OSNR when the new light-path is set up. Second, the set of available wavelengths over the shortest path route are determined for the connection request. Third, consider the new light-path is going to be set up on available wavelength λ_j. There are a group of LPIs that their OSNR would be degraded if the new light-path were set up on λ_j. For every LPI$_i$ in this group, the value of $\Delta OSNR$ (LPI$_i$)=$OSNR_{Current}$(LPI$_i$)– $OSNR_{Threshold}$ is computed, where $OSNR_{Threshold}$ is the minimum acceptable OSNR by the receiver, ΔOSNR is the residual acceptable OSNR remaining for LPI$_i$, and $OSNR_{Current}$(LPI$_i$) is the current OSNR of LPI$_i$. Fourth, CIA relevant to λ_j is obtained by the summation of 1/$\Delta OSNR$ values for each LPI in the group. Fifth, the wavelength λ_k with the smallest CIA is chosen for the light-path setup. Notice a light-path becomes more fragile if its $\Delta OSNR$ decreases. Therefore, smaller CIA leads to less fragile light-path setup. Finally, the OSNR of the new light-path on λ_k is computed. If the OSNR is acceptable, the OSNR values of already established light-paths are examined as well. If all these OSNRs are also acceptable, the new light-path is successfully set up. Otherwise, it is blocked. To compute OSNR, different impairments are considered including ASE noise; co-wavelength, self-wavelength and neighbour crosstalk of OXCs, and attenuations caused by MUX/DEMUX, switch fabric and optical fiber. Note that, [22] uses EDFAs with Automatic Gain Control (AGC) to avoid gain changes in EDFAs.

2) Distributed techniques: Here, the RWA techniques are studied based on the metric used for evaluating QoT.

a) QoT Evaluation with BER: In [24], mathematical models have been provided to estimate power level of optical signal, power level of ASE noise, and power level of intra-channel crosstalk at the output of a given intermediate OXC on a given wavelength. These models consider losses and gains of various network components (e.g., fibers, Erbium-Doped Fiber Amplifier (EDFA) amplifiers [47], switching elements in OXCs, taps in OXCs, multiplexers in OXCs, de-multiplexers in OXCs) through the network. On call arrival, the shortest path routing with the First-Fit technique are used for finding a candidate light-path. Then, a BER module estimates BER for the candidate light-path at the destination node. This module considers losses and gains in the network components traversed along the light-path, variances of ASE noise and intra-channel crosstalk generated in EDFA amplifiers and OXCs, and variances of thermal and shot noises. The candidate light-path is acceptable if its BER is lower than a given threshold. Otherwise, if no acceptable light-path can be found, the call is blocked. In [24], there is no inline amplification on transmission links due to short distances. However, OXCs employ EDFA amplification as [90].

In [102], pure RWA with the FF wavelength assignment technique determines a candidate light-path for a given connection request. Then, its BER is estimated at the destination node for accepting or rejecting the candidate light-path, where BER is computed using OSNR [4] at the destination node and OSNR is computed based on noise figure. The connection request is blocked if either there is no wavelength available or if the BERs for all available wavelengths are above a given threshold. Here, the following impairments are considered for computing BER: amplifier noise accumulation, amplifier gain saturation, wavelength dependent gain and losses along light-paths (including linear loss of the switch plus the multiplexer loss, and linear loss of the demultiplexer plus the switch loss, linear loss of the transmission fiber plus the input and output tap losses). Notice OXCs use EDFAs inside as in [90].

The FWM nonlinearity impairment is the only impairment evaluated in [40] in order to obtain BER. It is assumed that (ideal) EDFA amplifiers completely compensate fiber losses. Two algorithms are investigated: (1) the effect of FWM crosstalk is examined only on candidate light-path; and (2) the effect of FWM crosstalk is estimated on the pre-established light-paths that share links with the candidate light-path as well as the candidate light-path itself. Clearly, the latter can provide better performance results, at the expense of a high blocking rate. After determining a light-path using a pure RWA, its BER is examined. If BER is greater than a given threshold for two or more wavelengths, one with the smallest BER is accepted for establishment. If no acceptable BER can be found, the connection is blocked.

In [48], ISI, ASE noise, inter-channel crosstalk, and intra-channel crosstalk impairments are used to compute BER of a light-path after pure RWA, where BER is computed similar to [92]. For each source-destination pair, a set of K alternate routes is predetermined, where probability p_i is associated to alternate route R_i. At the initialization, this probability is equal to 1/K for all alternate routes. Upon a call request arrival between source s to destination d, source s selects route $R_j$among the alternate routes with probability p_j. Using the First-Fit technique, a tentative wavelength is selected. If this wavelength is continuous between source s to destination d on route R_j (this continuity is determined by a distributed manner) and BER on this wavelength is acceptable, the suitable light-path is setup. If the light-path does not satisfy a given required BER, the RWA process is repeated by picking another wavelength in sequence. If there is no suitable wavelength on route R_j, the call is blocked. When a call is accepted on route R_j, the parameter $p_j$in source s is increased, and the associated probabilities of other alternate routes in source s are decreased. By this, route R_j is motivated to be used later on. Otherwise, when no light-path can be found on route R_j, the parameter $p_j$in source s is reduced and the associated probabilities of other alternate routes source s are increased. By this way, route R_j is penalized to be used for next coming calls. The physical parameters are selected to model large-scale metropolitan networks with SMF fiber and full post-dispersion compensation.

In [105], intra-channel crosstalk and (EDFA) ASE noise impairments are used for BER evaluation for a candidate light-path after pure RWA. Three RWA algorithms are evaluated. In Impairment-Based Shortest Path (IBSP), after the arrival of a call, the available shortest paths for each wavelength are found. Then, the light-path with a wavelength with the smallest distance is chosen for BER evaluation. If the light-path has an acceptable BER, it is accepted. Otherwise, another light-path is picked and this algorithm is repeated. If no light-path meets the required BER, the call is blocked. In Impairment-Based First-Fit (IBFF), instead of selecting a wavelength with the shortest distance, the First-Fit technique selects the wavelength starting from the lowest-numbered wavelength until all wavelengths are examined. Other steps are similar to IBSP. In Impairment-Based Random (IBRAND), a wavelength is selected randomly to estimate its BER until all wavelengths are examined. Other steps are similar to IBSP. Since IBSP selects the smallest distance for a call, its accumulated ASE noise and coupled intra-channel crosstalk is smaller than other techniques. Therefore, blocking probability is the best for IBSP.

The distributed Create-and-Wait (CW) scheme has been designed in [106]. Upon a connection request arrival, the BER of a candidate light-path (found from a shortest path and an available wavelength) is estimated from the OSNR level at the destination node of the candidate light-path. The parameters relevant to OSNR level are continuously updated by monitoring equipments and flooded in the network by a routing protocol in real time. If the estimated BER does not meet a pre-defined BER threshold, the procedure is repeated to find another candidate light-path. Otherwise, the candidate light-path is set up. Before sending data on the setup light-path, CW transmits probe traffic over the setup light-path. Then, the BER of the probe traffic is measured at the destination node. The candidate light-path is considered suitable if the measured BER at the destination is acceptable. Then, client traffic can be transmitted. Otherwise, the setup light-path is torn down and the procedure of RWA is started again on a different route and wavelength. The drawback of this technique is its dynamic reconfigurations (due to frequent light-path setups and terminations) required in the network in order to set up an acceptable light-path, especially at heavy traffic loads at which BER may not be acceptable on the probe traffic. As stated in Section II, this may result in frequent network transient dynamics that would degrade the performance of wavelength channels.

The QoT-aware RWA proposed in [107] considers the variances of ASE, shot noise, thermal noise, and intra-channel crosstalk caused by switching component in optical switches, and crosstalk due to multiplexer/demultiplexers in order to compute BER. This article presents power level model when having SRS-induced crosstalk and without having SRS-induced crosstalk. On arrival a connection request, a light-path based on fixed shortest path routing, and considering either first-fit or random wavelength assignment is found. If no free wavelength is available, the connection request is blocked. Otherwise, BER at the destination node of this connection is estimated. To estimate BER, power model of SRS-induced crosstalk is considered. If the receiver BER associated with this light-path is less than a given threshold, the light-path is established; otherwise, it is blocked. It is shown that the presence of both intra-channel and SRS-induced crosstalk increases blocking probability. Whereas SRS does not contribute to BER-related blocking probability at the absence of intra-channel crosstalk. The optical switch architecture is the same as the switch architecture in [90]. Based on this architecture, it is assumed that the overall gain of optical switches compensates for the transmission losses, and therefore, no in-line EDFAs are used.

b) QoT Evaluation with power level: The objective of [108] is to maintain an acceptable level of optical power (not the maximum power) and adequate OSNR all over the network. Mathematical models have been provided for computing power sensitivity level in any component based on ASE noise, switch loss, and amplifier gain. The model is for cascaded amplifiers on each fiber. The k-shortest path and the First-Fit techniques are used for RWA. After determining a light-path, an iterative method is used to find a suitable transmitting power (starting from -30dBm and increasing 1dBm per iteration) for the light-path establishment. The transmitting power is limited to a maximum threshold value, where this constraint guarantees to minimize non-linear physical impairments because the aggregated power on any link is limited to the maximum threshold value. Under each transmitting power, the power of every network component is also verified to be higher than its sensitivity level in order to assure the detection of the optical signal by all optical devices. If a suitable transmission power can be found for a light-path that satisfies all the sensitivity levels, the light-path can be established. Notice the OXC switch architecture is the same as in [90].

In [21], the power level for an individual signal is maintained in such a way that the aggregated power on a fiber does not exceed a certain threshold. This is because saturation in an amplifier happens when the total input power of the amplifier exceeds a given threshold. When saturation occurs, the amplifier cannot work at its full capacity so that one individual connection with a high signal power may saturate the amplifier and reduce the gain for other signals sharing the same amplifier. Once a connection request arrives, a source node tries to find routes in sequence using fixed alternate routing mechanism with a valid wavelength (i.e., K shortest paths). If no available route can be found, the request is blocked. When saturation happens on the direct route (the first shortest path), the connection request along the direct route is blocked and an alternate route is chosen by the following mechanism. For each alternate route R_i(where $2 \leq i \leq K$), the transmission power of each intermediate optical switch on route R_i is computed and then the maximum transmission power is found throughout R_i. This maximum value is also found among other alternate routes. Finally, the path with the smallest maximum transmission power of all the candidate routes is chosen, thus avoiding saturation in amplifiers.

A QoT-aware RWA technique based on the meta-heuristic ant colony optimization has been suggested in [59], [111], where mobile ants are used to explore the network. Each node maintains a table of fixed k=3 shortest path routes from each source to each destination node. The ASE noise is considered to be the dominant impairment in network. Since this technique controls the maximum power used in every component to be limited, fiber nonlinearities can be indirectly managed due to their dependence on the signal power. At regular intervals, a forward ant is launched from a random source node to a random destination node. An ant only carries on its memory the node identification of each node that it passes by. During its trip from source to destination, the forward ant collects the label of each intermediate node where it passes by and puts the label in its memory. At each intermediate node, the forward ant chooses the next hop based on the power entering each neighbour link, maximum aggregate power on a link, and the visited/non-visited status of neighbour links. When the forward ant arrives at the destination, it becomes a backward ant and returns to the source using the same path followed by the forward ant. At intermediate node i, the backward ant updates the local parametric model (including average length of the paths followed by the ant from current i to the destination, the best value of path length found for this destination, etc.), and routing table for all entries relative to the destination. This update occurs when the evaluation of sub-path traced by the ant is good enough. Once a connection arrives, a Path message is sent from the ingress to the egress node for establishing a light-path. According to the destination node, the Path message picks the next hop neighbour node with the highest level of pheromone. When the Path message arrives at the egress, it checks if there are free wavelengths through all links traversed. If there is a route and a wavelength (found from the First-Fit mechanism) to make a light-path, the egress node sets up the light-path provided that the light-path satisfies the minimum power (computed based on ASE) and maximum power constraints, and the already setup light-paths are not violating the minimum and maximum power constraints. Notice the OXC switch architecture is the same as in [90].

c) QoT Evaluation with OSNR: A QoT-aware RWA has been presented in [112]-[113] that first finds a candidate light-path LP on wavelength λ based on the shortest path scheme, and then calculates its PMD and OSNR based on the method provided in [90]. If OSNR and PMD values are acceptable, the light-path is setup and data can be immediately transmitted. After establishing the light-path, an intra-channel crosstalk risk parameter is estimated at each node v along LP on wavelength λ. The total intra-channel crosstalk noise that can be tolerated along LP is computed based on a threshold OSNR parameter and the OSNR of LP. This crosstalk toleration is proportionally broken among all nodes along LP, and therefore, a crosstalk bound is assigned to each intermediate node v along LP. If the intra-channel crosstalk noise generated by node v on wavelength λ is greater than its predetermined bound, node v is called positive risk. On the other hand, if for all light-paths passing through node v on wavelength λ, the generated crosstalk is smaller than its predetermined bound, then node v is called crosstalk *risk-free*. If there are some nodes along LP which are not crosstalk risk-free, a rerouting procedure is used (as an active rerouting) to reduce the crosstalk risks of the nodes by migrating some of the light-paths that pass through the nodes. Light-path rerouting means the action of changing the physical path and/or the wavelength(s) of an established light-path. It is shown that this technique can reduce blocking probability and crosstalk risk in each node. In addition, it can improve the fairness of QoT degradation among light-paths, where the OSNR degradation among light-paths with different hop numbers becomes closer to each other. The network infrastructure (including switch architectures and amplifiers architectures on fibers) is the same as in [90].

In [114], a combination of different techniques has been used to establish class-based connection requests (CRs), namely High Priority (HP) and Low Priority (LP) connections. Each ingress node includes m HP buffers and m LP buffers (for m egress nodes) to save the CRs that cannot be setup due to resources lack. When network resources become available, the CR that has waited for a long time is scheduled to be set up. Scheduling starts from HP buffers and when there is no HP connection for setup, the LP connection requests are evaluated. Two patience times for waiting in HP and LP buffers are defined for HP and LP CRs, respectively. When a CR cannot be set up within its patience time, it is blocked. For wavelength assignment, a wavelength ordering technique is used and the order of wavelengths are saved in set V in such a way that the wavelengths located at the beginning of V are from edge wavelengths in the wavelength spectrum (far from each other) and the wavelengths located at the end of V are chosen from the center of the spectrum (close to each other). Based on the combination of PMD and CD parameters of links, k routes between any source-destination pair x and y are ranked in an ascending order and saved in set $R_{x,y}$ so that the routes at the beginning of this set have small dispersion and the routes at the end of this set have high dispersion, called alternate least dispersion routing. When establishing an HP connection between nodes x and y, the routes starting from the beginning of set $R_{x,y}$ are evaluated. On the other hand, when routing an LP connection, the routes starting from the end of set $R_{x,y}$ are evaluated. Similarly, for wavelength assignment to an HP connection, set V is searched from the beginning and the feasible wavelength is found (first-fit). Whereas for an LP connection, V is searched starting from the end and the feasible wavelength is assigned to the connection (called last-fit). After determining a candidate light-path, its OSNR is evaluated at the destination node (according to the method in [90]) to be higher than a given threshold. Two separate thresholds are utilized for HP and LP connections, where OSNR threshold for an HP connection is higher than for an LP connection. If OSNR is not acceptable for the candidate light-path, a new wavelength/route is determined. Otherwise, the OSNR of existing light-paths that may be degraded are re-evaluated. If set up of the candidate light-path never leads to unacceptable OSNR for the existing light-paths, the candidate light-path is set up. When an HP connection cannot be set up, an existing LP light-path is allowed to be pre-empted to accommodate the HP connection. However, the pre-emption happens when the patience time for the HP connection is close to be over. In this case, the LP light-path with the least utilization of network bandwidth is pre-empted. Notice switches and amplifiers architectures are the same as in [90].

In [90], [115]-[116], the OSNR and PMD effects are estimated at the physical layer at destination node, and then considered as the effective metrics for a light-path admission. For PMD, the well-known pulse broadening relation is used. For modelling OSNR, an iterative method is used to compute the power of optical signal and power noises propagating through the light-path. At each intermediate node, the OSNR model computes power of optical signal at the output of the node, power of node noises (including intra-channel crosstalk and ASE noise of EDFAs), and power of DRA noises on fiber links (including ASE noise and Multi-Path Interference (MPI)). Finally at the destination node, OSNR is computed as the signal power arriving at the destination node divided by the sum of power of DRA noise and power of node noise at the destination node. For a call, the network layer first chooses a candidate light-path and then the physical layer verifies its quality. If both PMD and OSNR quality requirements are met, the candidate light-path is established. Otherwise, another candidate light-path should be chosen. Two RWA algorithms have been studied as the impairment-aware best path algorithm and impairment-aware First-Fit technique. In the former, for each connection request, the candidate light-path is the shortest one among shortest paths on all free wavelengths. However, in the latter, finding light-paths (with shortest path) starts from the first wavelength in wavelength spectrum and continues toward the last wavelength in sequence. The first light-path that can lead to acceptable QoT is admitted. Therefore, the former has a nature of allocating wavelengths without order, but chooses the light-path with minimum distance from all available shortest paths. The results show better blocking for the impairment-aware best path algorithm. In [90], [115]-[116], for every OXC with size $m \times m$, there are m small-signal gain EDFA amplifiers at the input side and m small-signal gain EDFA amplifiers at the output side of the OXC. The EDFAs on the input side compensate the signal attenuation along the input fibers and tap losses; whereas the EDFAs on the output side compensate the losses occurred during switching in the OXC. For a fiber link between any two nodes, DRA amplifiers with 82 km spacing are employed. Each amplification span includes 70 km of SSMF whose dispersion and dispersion slope are compensated by 12 km of DCF.

d) QoT Evaluation with OSNR and EL: Three measurement-based techniques based on probe traffic have been suggested in [52], [117]. First, in Probe-based Scheme (PS), a pure RWA is first performed to set up a light-path between a source and a destination. The light-path is not activated yet. Before sending client data traffic, probe traffic is first transmitted from the source to the destination through the established light-path. Then, QoT is verified through measurements (i.e., BER or OSNR) on the probe traffic at the destination node. If QoT is acceptable, the light-path is activated and client data traffic is transmitted along the setup light-path. Otherwise, the RWA procedure is re-performed to set up a new light-path. Second, in signalling-based probe scheme (S-PS), QoT estimation is performed during signalling using RSVP-TE. Upon a light-path request from a source to a destination, the source node sends a Path message toward the destination node. The Path message gathers information relevant to available wavelengths and QoT (i.e., OSNR or EL) of links in each intermediate node. Each intermediate node traversed by the Path message appends the expected QoT related to its downstream link in the Path message. Upon the receipt of the Path message, the destination node computes the light-path QoT metric (i.e., OSNR or EL) by combining the parameters associated with the traversed links and nodes. For EL-based QoT, let x be the computed EL, and $M_1$and M_2be two mileage thresholds, where M_1 shows the length of the shortest unacceptable path, and M_2denotes the longest acceptable path. If $x \leq M_1$ (i.e., QoT is acceptable), data is transmitted immediately after establishing the light-path without the need for sending probe traffic. If $x \geq M_2$ (i.e., QoT is unacceptable), the light-path setup is blocked. Then RWA process is repeated. When $M_1<x<M_2$(i.e., critical range), probe traffic is transmitted over the setup light-path and the QoT (i.e., BER or OSNR) of the probe traffic is measured at the destination node. If QoT is acceptable, the light-path is activated and client data traffic is transmitted along the setup light-path. Third, in Routing-based Probe Scheme (R-PS), upon a light-path request from a source to a destination, QoT (i.e., OSNR or EL) is estimated. If QoT is unacceptable, another light-path is found. If QoT is acceptable, the light-path is set up and client traffic is transmitted at once. Otherwise in critical range, probe traffic is sent along the light-path. If the QoT of the probe traffic is acceptable, then the light-path is activated for data transmission. In R-PS, QoT estimation parameters associated with each link are advertised using OSPF-TE signalling. It is shown that R-PS can provide better performance results in general. As stated in Sections II and V.A.2.a, establishing a light-path, then probing traffic in order to find whether it is acceptable or not, then

terminating the light-path if it is not acceptable, and repeating the whole process again and again will increase network transient dynamics and degrade quality of signal transmission on wavelength channels.

e) QoT Evaluation with EL: Two simple probe-based techniques have been presented under GMPLS signalling in [118], where no impairment is evaluated analytically at the light-path establishment phase. In the first technique, there is a limit on the light-path physical length, where a static Equivalent Length (EL) QoT parameter is used in routing. In this technique, equivalent length (see Section II) values of traversed links are combined to compute a light-path QoT. If the total equivalent length is smaller than a threshold value, the light-path set up can be triggered. Then, the probe traffic is sent over the established (but not yet activated) light-path. Whereas, the second technique does not consider any limit. After a light-path establishment based on shortest-hop and first-fit wavelength assignment for a given connection request (but not activated for traffic transmission yet), probe traffic is sent over the established light-path. At the destination node, an OSNR-based model is used to emulate QoT considering ASE, PMD, chromatic dispersion, and self-phase modulation impairments. Under both techniques, if QoT is not acceptable or there are not available resources in network, connection request is blocked and then up to two additional setup attempts are started. Otherwise, data transmission is activated on the established light-path.

f) QoT Evaluation with crosstalk: In [119], a Maximum Tolerable Impairment (MTI) threshold is assigned to each node that shows how much intra-channel crosstalk that node can tolerate. Notice deploying automatic gain control EDFA at each transmission link, the fluctuation of channel noise is mainly caused by in-band crosstalk. The RWA in this technique is based on GMPLS signalling in which Path messages are extended to carry impairment information. On receipt of a connection setup between a source and a destination, a Path message is sent from the source to the destination along the shortest path route. This message includes an Available Continuous Wavelength Set (ACWS) initialized by the source node according to its available wavelengths at the output port toward the destination. When an intermediate node receives this message, it updates ACWS according to its available wavelengths so that a continuous wavelength can be provided. Then, for each wavelength in ACWS, it is checked whether this wavelength leads to unacceptable intra-channel crosstalk in the intermediate node or not. For intra-channel crosstalk, both co-wavelength and adjacent-wavelength impacts are evaluated. If this wavelength leads to higher intra-channel crosstalk than MTI, it is removed from ACWS. The intermediate node then forwards the Path message to it next hop node with the updated ACWS. The destination node estimates BER for each wavelength in ACWS and those wavelengths that have acceptable BER (i.e., smaller than a threshold BER) are kept and the rest are removed from ACWS. Note BER is estimated based on ASE and intra-channel crosstalk impairments. Then, a wavelength can be picked from ACWS based on one of four schemes: Best Prefer (highest BER), Worst Prefer with lowest (acceptable) BER, random, and first fit. Then, the light-path with the chosen wavelength is setup. Performance evaluations show that the first fit wavelength selection from ACWS leads to the smallest call blocking.

The Adaptive wavelength assignment with First Fit Wavelength Spectrum Separation (AFFwSS) technique based on online wavelength ordering has been proposed in [120]. This technique combines the FFWO [123] and FFWSS [124] wavelength assignment techniques in such a way that it switches between them based on the instantaneous network physical impairment severity, i.e., for small physical impairments FFWO and for large impairments FFWSS are used, respectively. This technique has strong advantages in terms of blocking probability over FFWO and FFWSS. Similar to FFWSS, a penalty factor is defined that counts the relative effects of each switch crosstalk (different crosstalk terms in an OXC has been stated in Section III). The penalty factor for a given wavelength in a node is computed based on the fabric crosstalk and adjacent port crosstalk power level attenuations with respect to the main signal, and the effect of FWM and XPM. On call arrival, the source node finds a shortest path route. Then, each node on the route calculates its own penalty factor for every free wavelength. After computing penalty factor for each node, total penalty factor for the route is obtained. To compute total penalty factor, for every wavelength, the largest penalty factor among all nodes on the route is first obtained. Then, the smallest penalty factor among them gives the total penalty factor. If the total penalty factor is smaller than a given threshold, wavelength assignment is based on FFWO. Otherwise, it is based on FFWSS.

g) QoT Evaluation with Q-factor: The QoT-aware RWA proposed in [122] includes three parts as: Physically Aware Routing (PAR) algorithm, Physically Aware Backward Reservation (PABR) protocol, and Quality-aware First–Fit (QFF) wavelength assignment algorithm. The PAR uses a shortest path algorithm in which the cost of a link is a function of the number of allocated wavelengths on that link. Then, a number of candidate paths are determined where each candidate path satisfies the ASE constraint so that the accumulated ASE along the candidate path should be smaller than a given threshold. Then, the source node starts the PABR protocol and sends probe messages on these candidate paths in parallel. When a probe message is passing through an intermediate node, the intermediate node records which wavelengths have already been used in the probe message and also checks whether the establishment of a new light-path can cause unacceptable signal degradation to existing light-paths. If yes, this candidate path is discarded. Upon the arrival of the probe message, the destination node executes the QFF algorithm to estimate the signal qualities of possible light-paths (with the same path but different wavelengths) and chooses a candidate light-path using the FF wavelength assignment with acceptable signal quality. Then, the destination node sends a reservation message upstream toward the source node to reserve network resource and establish the connection. Each span in the network consists of a long NZDSF or SMF fiber, a short DCF fiber, and an EDFA as an in-line amplifier.

B. Indirect Modelling of Impairments

The following schemes can be found for the indirect modelling of impairments under the QoT after pure RWA category:

1) Centralized techniques: In the following subsection, RWA is reviewed based on the metric used for QoT evaluation.

a) QoT Evaluation with crosstalk: In [34], a crosstalk-aware wavelength assignment algorithm has been proposed by which the wavelength for a light-path is selected in such a way that the light-path encounters least amount of crosstalk components (see Section III). Note that more crosstalk components (co-wavelength crosstalk, self crosstalk, and neighbour-port crosstalk) in each switch lead to worsen BER performance. On the other hand, BER computation for crosstalk on each feasible wavelength for a light-path establishment is time-consuming. Therefore instead of computing BER for a light-path with a given wavelength, the weighted counts of the number of crosstalk components (i.e., co-wavelength crosstalk components, self crosstalk components, and neighbour-port crosstalk components) are summed on the wavelength in all OXCs along the light-path, thus reducing computation time [34]. The weights are set in such a way that crosstalk components with stronger leak are given more weights. This weighting helps to find the wavelength that leads to least amount of generated crosstalk. Then, the wavelength with the minimum summation is chosen. If there are multiples of such wavelengths, one of the four crosstalk-aware techniques (i.e., random pick, First-Fit, most used, and least used) can be used to select one wavelength. After finding a light-path using the counting process, the BER of the light-path is estimated. If the acceptance of the new light-path will either lead to an unsatisfactory BER in the new light-path itself or cause an unsatisfactory BER on any of the previously established light-paths, the new light-path is blocked. The crosstalk-aware random pick technique leads to the best physical blocking because it reduces intra-channel crosstalk, but it has the worst wavelength blocking probability, overall not good as others. In the proposed work, EDFAs with AGC are evenly placed on transmission links in order to avoid gain changes in EDFAs. In addition, amplifier-free OXCs are used in [34].

2) Distributed techniques: Here, the RWA techniques are reviewed based on the metric used for QoT evaluation.

a) QoT Evaluation with crosstalk: In [123]-[124], the architecture of OXCs is the same as in [90] with EDFA amplifiers used inside switch. It is also assumed that dispersion is fully compensated by post compensation. Two wavelength ordering schemes have been suggested for wavelength assignment process in order to relieve crosstalk impairment in switches as follows:

1) Wavelength Assignment using First Fit with Wavelength Ordering (FFWO) [123]: First, all nodes compute a pre-ordering of the wavelength spectrum in off-line. Then, at run time, every node picks the first wavelength in the ordered list that is available through the entire route for a call. The algorithm of ordering wavelengths places first on the list the wavelengths that are not adjacent to any wavelength previously used. When no such wavelengths remain, the wavelength that has only one adjacency with a wavelength that is already in the list is selected. Finally, the wavelengths sandwiched between already lit channels are selected. For eight wavelengths, this algorithm results in the ordering of (1, 8, 4, 6, 3, 7, 2, and 5). This scheme is an offline wavelength ordering technique. By FFWO, no adjacent-port crosstalk happens until more than half of the wavelengths are allocated.
2) Wavelength Assignment using First Fit with Wavelength Spectrum Separation (FFWSS) [124]: This scheme is an online wavelength ordering technique, where all unused wavelengths are sorted during light-path setup to find a wavelength with the smallest performance penalty factor that represents the level of impairment normalized to intra-channel crosstalk. Here, instead of estimating the actual BER for each candidate wavelength and other affected wavelengths in the entire network, a penalty factor is defined that counts the relative effects of each crosstalk term in an OXC (see Section III for switch crosstalk terms). The penalty factor for a given wavelength in a node is computed based on the intra-channel crosstalk and adjacent port crosstalk power level attenuations with respect to the main signal. The idea behind this technique is that establishing light-paths based on the wavelengths with the smallest total penalty factor are least likely to be blocked. Along the path obtained from shortest path fixed routing for a connection request, each node counts crosstalk penalty for each one of its available wavelengths. Then, one wavelength with the minimum total penalty factor through the chosen path is picked for light-path setup.

The Minimum Crosstalk (MC) QoT-aware RWA scheme [77] finds candidate light-paths using a shortest path algorithm (with link cost equal to the length of link) for each wavelength. For each candidate light-path setup on wavelength j, the number of intra-channel crosstalk components at intermediate nodes along a candidate light-path is counted. Two types of crosstalk components are considered at each intermediate node as (1) the number of light-paths established on the same wavelength to account for switch port crosstalk; and (2) the number of light-paths established on adjacent wavelengths of wavelength j to account for adjacent crosstalk. Finally, the candidate light-path with the smallest crosstalk intensity is chosen for setup.

VI. Discussions

This article has reviewed the QoT-aware RWA techniques appropriate for dynamic systems. Two major categories of QoT-aware RWA algorithms have been detailed, where each category has been divided into two sub-categories. Under a direct modelling, the impairment model is directly incorporated in the RWA process. In an indirect modelling, a network parameter (say physical length, congestion, number of switches, etc.) that has correlation with impairment is incorporated in the RWA procedure. The indirect modelling aims to minimize the complexity of the RWA operation.

Clearly, QoT-aware RWA techniques are more complex than pure RWA techniques. In pure RWA, as soon as finding a feasible light-path it can be setup promptly. However, QoT-aware RWA should perform exhaustive computations required to find a light-path (among all feasible light-paths) that satisfies the desired BER requirements. In addition, a good QoT-aware RWA should perform additional computations to check the quality of existing established light-paths in order to make sure that the quality of the existing light-paths will never go below a given threshold. This is because a new light-path (with an acceptable quality) that is going to be setup may provoke so much crosstalk in the network in such a way that the quality of the existing light-paths drops below a given threshold.

The "QoT Evaluation after RWA" category is simple but it may lead to a high computational complexity. This is because to find a suitable light-path, many different combinations of light-paths should be investigated. Clearly, this technique may not be suitable for connection requests that must be established in a very short time, for instance, high priority emergency connection requests.

On the other hand, in the "Integrated QoT and RWA" category two challenges still exist: (1) The complexity of designing mathematical models used for computing of links costs because linear and non-linear impairments may not be combined together in order to represent all the impairments in a single cost parameter, thus limiting the scalability of this category; (2) The computation time of cost of links in a dynamic way according to physical impairments due to the variation of network physical parameters with any light-path setup and release. To reduce the computation time, indirect modelling of impairments can be used, where network parameters such as congestion, link length, etc. can be used for links costs. This is because of their correlation with physical impairments.

Note that it may not be possible to compare all the QoT-aware RWA schemes with each other due to their inherent implementations. Since the physical parameters used in the reviewed articles are totally different, a general comparison has been provided in the following based on different aspects as traffic class, buffering of connection request, routing, wavelength assignment, rerouting, fairness, complexity, blocking, and so on.

Traffic Class: Most of the works consider single class traffic, except [52], [69]-[70], [97], [114], [117] that has provided a QoT-aware RWA technique for differentiated class of connection requests. Note that pure RWA has been proposed for differentiated class of connection requests in various works, e.g., [8], [127]-[128]. For different connection request classes, different threshold values are used, e.g., different OSNR threshold values have been used for premium and best effort classes in [52], [114]. It seems that QoT-aware RWA should consider differentiation of connection requests because it is required for different applications that need different levels of quality of service for their traffic.

Connection Buffering: In [28], [96], [114], connection requests information are saved in a First Come First Served buffer and then established in sequence from the head of the buffer. It is noted that in connection buffering, the information of connection requests are only saved in the buffer and no traffic transmission is initiated until it is completely set up. Saving connection requests can improve blocking probability. If a new connection request that cannot be immediately established when it arrives, it is not blocked immediately. Instead, it is saved in a buffer and then it can be established whenever enough resources become available. Buffering imposes setup latency parameter in the network, where connection requests that cannot be setup within a given time are blocked. This is because of the sensitivity of some applications on the setup time.

Single-path vs. Alternate Routing: The common routing schemes are based on either shortest path or *k*-shortest path (alternate routing). Clearly, the routing in these schemes can be performed offline which simplifies the operation of RWA. Single-path routing leads to worse performance results than alternate routing due to many routes available under alternate routing. Some techniques have used adaptive shortest path in which a route is determined based on a network status, e.g., [97] which operates based on least congested routing. Obviously, this type of routing could be more effective than the common techniques but it is time consuming compared with the shortest path and *k*-shortest path techniques. In general, shortest path routing techniques can lead to select light-paths with small PMD, CD, ASE noises. On the other hand, a shortest hop routing can result in obtaining a light-path with a small intra-channel crosstalk because the light-path will cross a small number of all-optical switches. A combined routing based on PMD and CD dispersions have been used in [114] that sorts alternate routes based on their dispersion in an offline mode. Then, suitable routes with least dispersion are chosen for high priority connections and most dispersion routes for low priority connections.

Wavelength Assignment: Many techniques described in [24], [50], [79], [90]-[91], [102], [108] have used the FF wavelength assignment technique. Some techniques described in [23], [34], [105] have used the random wavelength assignment technique. The FF is usually preferred in practice because of its low computation complexity, efficiency in the utilization of wavelengths, simplicity to be implemented in hardware, fairness, and finally lower blocking probability [3], [6], [20]. Although FF is better than Random in ideal wavelength routed networks (i.e., when no physical impairment is assumed for the network) [24], [28], the Random technique outperforms FF when transmission impairments are considered in an RWA problem [24], [28]. This is because both intra-channel and inter-channel crosstalk become high when FF is used in the wavelength assignment process.

Wavelength Ordering: To reduce the effect of crosstalk (both adjacent-port in OXCs and inter-channel), wavelength ordering techniques have been utilized in the RWA process [28], [114], [120], [123]-[124] that make wavelengths passing through an OXC sufficiently far apart from each other. Using wavelength ordering, the wavelength considered for a light-path setup would find a small number of adjacent-port crosstalk terms and inter-channel crosstalk. Wavelength ordering could be either offline or online [28]. Offline ordering is only performed once and the RWA should choose a wavelength in sequence from the ordered list. On the other hand, on-line ordering can minimize the crosstalk for the current network state. However, online ordering may destroy not only the sequence in which the wavelengths are used but also the property of the First-Fit wavelength assignment technique that attempts to pack the traffic on as small number of wavelengths [28]. In addition, the complexity of the online ordering is more than the offline ordering. Wavelength ordering at system level is similar to wavelength dilation at device level [4].

Wavelength Conversion: As reviewed, no work has included all-optical wavelength conversion on the modelling of QoT-aware RWA, except [39], [97] that indirectly consider all-optical wavelength conversion in RWA. This could be due to the fact that many non-linear physical impairments are wavelength dependent, which makes difficult to model the computation of say OSNR over different wavelengths along a light-path. On the other hand, when the modelling of wavelength conversion is not necessary, one can find some techniques in which OXC nodes are equipped with all-optical wavelength converters e.g., [6], [39], [97], [129].

Rerouting: Rerouting used in [112]-[113] could be a viable and cost-effective mechanism to improve blocking performance and fairness. After establishing a light-path and estimating intra-channel crosstalk risks and finding the nodes that are positive crosstalk risk, a rerouting procedure is employed that reduces the crosstalk risk of the positive crosstalk risk nodes by migrating some of the light-paths that pass through these nodes. When rerouting, some of the light-paths which traverse through node v on a given wavelength with positive crosstalk risk status can become risk-free. The rerouting algorithm determines whether light-paths that pass through node v on the given wavelength can be rerouted or not. If yes, which new paths they can use. Among the new paths, those having the lowest risks can be selected. Note that rerouting of a given light-path will not happen before finding and establishing a new light-path. Rerouting of established light-paths can also be performed to accommodate new connection requests that are going to be blocked due to unacceptable quality of transmission [66]. This can be more effective when connection requests are prioritized. In this case, a low priority light-path should be rerouted if a high priority connection request cannot be established due to an unacceptable BER. In short, by rerouting of established connections, the usage of network resources can be optimized. Despite its effectiveness, rerouting may be time consuming which could not be suitable for delay-sensitive applications. In addition, rerouting may result in many reconfigurations in the network due to potential instabilities. On the other hand, some light-paths may need to be temporarily interrupted during rerouting. However, this may not be desirable by network operators because of the contract signed with the corresponding clients. Finally, network transient dynamics can be counted as another drawback for rerouting that not only leads to power transient dynamics in amplifiers (see Section II) but also results in bandwidth wastage. The reason for bandwidth wastage is due to the fact that during rerouting, the source node should append an End-Of-Transmission (EOT) control packet after sending the last packet on the old wavelength and should hold the first packet on the new wavelength for a guard time [130], where the EOT packet carries the notification information about the old and new light-paths toward the destination node. The guard time is necessary to prevent from data loss during the transient period of light-path migration.

Monitoring: Although the measurement of impairments through monitoring [50], [106] can provide accurate results, the monitoring may have two constraints [106]. First, its cost limits the number of monitoring points that can be employed in the network. Second, some impairments cannot be easily measured such as (1) BER performance: This cannot be calculated by counting received bits at the destination, because this operation is not real-time; and (2) Parameters like the CD slope, the effective area of the fiber non-linear index of crossed elements, or the CD contribution of crossed filters. This is why many researchers use modelling approaches to approximate a physical impairment.

Complexity of light-path setup: The evaluation of quality of transmission can be performed by two categories. Most of the QoT-aware RWA techniques lie in the first category that only evaluate the new light-path to have an acceptable quality. On the other hand, in the second category there are some techniques [22]-[23], [34], [40], [59], [66], [75], [111], [114] that not only evaluate the new light-path to have an acceptable quality but also they make sure that the setup of the new light-path will not enforce the quality of existing light-paths to drop below a given threshold. The second category is more appropriate than the first category for wavelength routed networks because it is not acceptable for an existing connection to find an undesirable quality after establishing a new light-path. However, the RWA in the second category is more complex than the first category and the time required to find a suitable light-path may be very long which may be undesirable for some delay-sensitive applications.

Complexity of impairments modelling: Different analytical models have been employed in literature for estimation of impairments. The complexity of these models varies from simple to complex as follows:

1) Some literatures utilize very complex models to estimate impairments. Examples are as following: (a) techniques such as [90], [106], [113]-[114] use the complex model in [90], developed based on the current network state. In [90], a number of complex integration equations must be solved in order to compute noise power generated by a DRA. Then, the model uses the DRA noise in a series of iterative equations to compute accumulated DRA noise power, accumulated node noise due to crosstalk, and propagating signal power along a light-path. Finally, OSNR can be calculated at the destination node to make decision about acceptance or rejection of only one candidate light-path. Clearly, this computation significantly increases light-path setup latency, especially when it is required to evaluate the OSNR of existing light-paths that share nodes or links with the candidate light-path; (b) when variances due to XPM and FWM are considered in Q-factor computation as in [66], the complex model provided in [68] could be utilized; (c) when considering both fiber nonlinearity and crosstalk at the same time as in [91]-[93], the complex model in [95] can be used; (d) when considering XPM, FWM, and SPM non-linear impairments at the same time as in [60], the complex models provided in [61]-[63] should be evaluated; and (e) when considering FWM, XPM, and amplifier gain saturation as in [75], the complex

modeling provided in [76] can be used, where the model in [76] uses the models of [62] and [63] for computing the effects of XPM and FWM impairments.

2) Some literatures employ models with a number of time-consuming computations as the following: (a) those works that consider ASE and switch crosstalk as in [23]-[24], [105], [107], use the model developed in [24]; (b) when considering ASE noise of cascaded amplifiers as in [59], [108], [111], the model developed in [109] could be used; and (c) when taking ASE noise, gain saturation, intra-channel crosstalk, PMD, and FWM all together into account as in [78]-[81], the model provided in [79] should be employed.
3) Some works use simple analytical models as the following: (a) the works in [28], [34], [48], [50], [102], [119] use BER analysis stated in [4]; (b) the work in [39] uses PMD computation mentioned in [4]; (c) the works in [34], [39], [73], [119] use the ASE formulation in [4]; (d) when considering signal power [21], the simple model presented in [110] can be used; and (e) when considering only FWM as in [40], the approximated model developed in [104] can be used.
4) To simplify the computation complexity, some works carry out offline pre-computations to provide a lookup table to be used in online light-path setup process. Examples are as following: (a) work in [25], [101] provide an offline simulation to obtain an empirical function for XPM effect and to create a lookup table in which OSNR is evaluated based on different parameters such as fiber characteristics, number of active wavelengths, length of fiber spans, and transmitter powers. Then, at light-path setup procedure, the lookup table is easily searched for OSNR based on the network status parameters at the time of light-path setup; (a) similarly, variance due to XPM and FWM nonlinearities based on the spectral positions of active wavelengths is pre-computed in offline [120] using the complex model presented in [121], and then saved in a lookup table to be used in light-path setup process; and (c) a similar simplification has also been used in [64] where CD and filter concatenation related Q-factors are pre-computed and then used in light-path setup process.

Light-path Choice: Some techniques try to find the best possible light-path with, e.g., the highest Q-factor [34], [60], [66], [91], the highest-OSNR [25], [101], the smallest BER [40], and the smallest maximum transmission power [21]. These techniques have high setup delay because all possible candidate light-paths must be examined before establishing a light-path with the best OSNR and Q-factor. The setup delay depends on the network topology and its scale could be even in seconds. In addition, maximizing Q factor cannot reduce blocking probability [28]. On the other hand, the technique described in [114] chooses the first candidate light-path that its OSNR is higher than a given threshold value for setup. There are works described in [69]-[70] that choose the candidate light-path with the closest acceptable BER to the connection request BER requirement.

Start of Data Transmission: Most of the QoT-aware RWA techniques operate on the idea of establishing of a light-path and then immediately sending traffic on the setup light-path. However, the techniques described in [52], [106], [117]-[118] first create a light-path and then send probe traffic on the setup light-path in order to make sure (in addition to the QoT estimation in the setup phase) that the setup light-path has a suitable QoT. Clearly, verification of the BER level of a created light-path increases setup delay. Moreover, many reserved resources can be wasted if verification is unsuccessful [106]. In addition, this can increase network transient dynamics and can degrade quality of wavelength channels.

Blocking Rate: Blocking rate of connection requests increases in all QoT-aware RWA techniques compared with pure RWA. This is because network resources may be available for a light-path setup but the quality of the light-path may not be acceptable. In short, blocking rate for a QoT-aware RWA technique is the sum of blocking due to unavailable resource plus blocking due to insufficient quality of a light-path to be setup. As discussed above, two categories are used for the evaluation of QoT. The first category evaluates QoT only for a candidate light-path, whereas the second category evaluates QoT both for candidate light-path and all pre-established light-paths. Obviously, the connection blocking rate of the second category could be more than the first one because a candidate light-path may have an acceptable QoT but its setup may degrade the quality of existing light-paths (an unacceptable issue).

Mixed-rate Traffic: Most works have considered single rate, single modulation format light-paths (i.e., homogenous system). On the other hand, there are few works that have considered mixed-rate traffic scenarios with different modulation formats [50], [73]. Simultaneous transmission of services with different edge transponder technologies increases the physical layer flexibility so that users are given the choice of installing their own transponders [73].

Gain Controlled Amplifiers: Some works have employed EDFAs with AGC to avoid gain changes in EDFAs during network transients, e.g., [22], [28], [34], [50], [91], [119]. Other works have assumed amplifiers are ideal without any transient.

Fairness: In addition to QoT-awareness, fairness could be an important property for an RWA algorithm, where fairness refers to how network resources are shared among users. It is desirable to design fair RWA algorithms that try to accommodate both (1) long-distance, high-noise, and high-crosstalk light-paths; and (2) short-distance, low-noise, and low-crosstalk light-paths. In addition, it is desired to design RWA algorithms that are fair with respect to the OSNR degradation. In [108], it is shown that by considering physical layer impairments in RWA, long-distance light-paths experience much more blocking than short-distance light-paths compared to the pure RWA case. In [91], the proposed fair QoT–aware adaptive RWA (i.e., MmQ, MmQ2) improves fairness in blocking probability and BER. Under MMQ2, the minimum Q-factor above a given threshold of all light-paths that have a common node with a tentative light-path is recorded. Then, the light-path that maximizes (over all possible wavelengths) these minimum Q factors is chosen for setup [91]. This method allows a short light-path to be setup only when number of wavelengths available on a tentative path

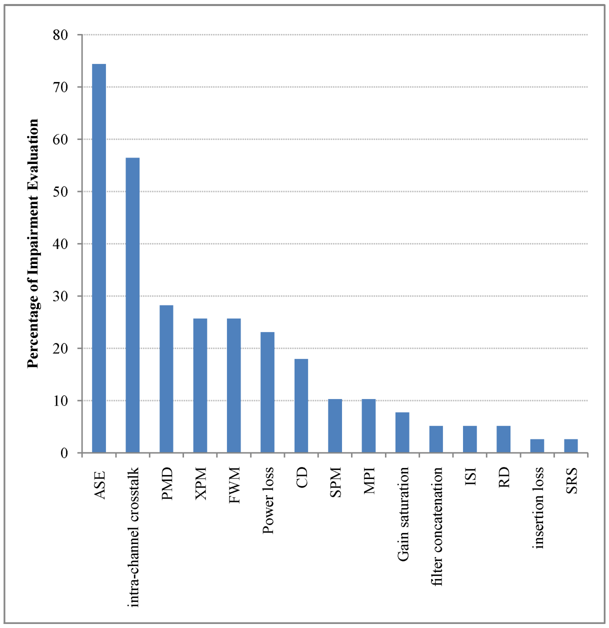

Fig. 2. Popularity of impairment evaluation in literature

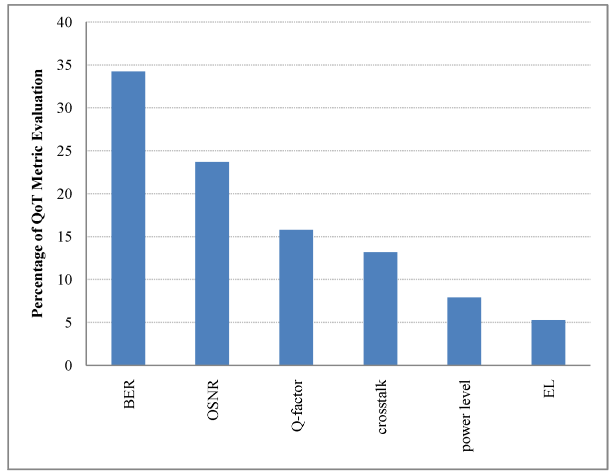

Fig. 3. Popularity of QoT metric evaluation to admit a candidate light-path in literature

is above a given threshold. This saves wavelength resources for long-hop light-paths. However, it may waste wavelength resources. In [112]-[113], the QoT-aware RWA estimates and reduces crosstalk risk at the routing process in such a way that the OSNR degradation among light-paths with different hop numbers becomes closer to each other, i.e., a fair OSNR degradation. Two algorithms can be found in [92], where one of them focuses on the selection of the light-path with the highest Q factor, and the other addresses the fairness issue and tries to minimize the impact of this light-path on the already established light-paths. The technique proposed in [112]-[113] has better fairness than MmQ2.

Validation of Analytical Models: There are some works that have validated estimated impairments obtained from analytical models. These estimators have been validated either using laboratory experiments e.g., [131]-[132] or simulation results, e.g., [133], or both e.g., [37], [134]-[135]. However, few of them have validated impairment models on light-paths. The accuracy of QoT formulation has been evaluated in [131], [133], where QoT is a function of parameters that accumulate along a light-path as OSNR, nonlinear phase, and residual chromatic dispersion. Similarly, the accuracy of QoT (computed based on OSNR, crosstalk, PMD, nonlinear phase, and accumulated dispersion on transmission and compensation fibers) is verified under different network heterogeneity (different mixed fiber types, different transmission distances, and varying neighbor channels propagating with an observed channel) and scenarios close to mesh networks (using a double loop), not point-to-point experimental/ simulation setups.

Indirect Cost Models: Different network parameters can be used as representatives for transmission impairments as follows:

1) Cost for nonlinearities could be congestion (occupancy of a link) of a path because highly loaded paths produce higher nonlinear impairments [75]. Therefore, with a lower congestion, RWA indirectly will pick a path with smaller nonlinearities and impairments.
2) One can use wavelength availability on a link as cost for amplifier saturation because link usage has a direct impact on amplifier saturation [79]-[80].
3) Cost for ASE noise could be based on (1) the number of amplifiers used along the link [18]; (2) link length [75], [79], and (3) link usage [79]-[80]. All these three cost refer to the number of ASE sources in a path. However, number of amplifiers used along the link could be a more accurate technique.
4) Cost for intra-channel crosstalk could be based on (1) number of light-paths crossing at the head and tail nodes of a link [77]; (2) weighted counts of the number of crosstalk components (co-wavelength crosstalk, self crosstalk, and neighbor-port crosstalk) [34]; (3) number of light-paths established on the same wavelength to account for switch port crosstalk [77]; (4) number of light-paths established on adjacent wavelengths of a given wavelength to account for neighbor-port crosstalk [77]; and (5) penalty factor [120]. The weighted counts of the number of crosstalk components could be more accurate because it accounts for all possible crosstalk sources in a switch.

Popularity of Impairments: Fig. 2 illustrates the percentages of linear and nonlinear impairments that have been evaluated in the literature, where performance monitoring techniques are excluded. Notice that this figure only depicts each specific impairment by itself. For example, if an article evaluates ISI impairment, it is shown in the figure as one work on ISI, and several effects (like SPM, CD, FC) that may cause ISI are not considered in the chart. As one can see, more than 74% of techniques evaluate ASE noise. The evaluation of intra-channel crosstalk, PMD, XPM, FWM, power loss, and CD are performed in almost 56%, 28%, 25%, 25%, 23%, and 18% of the literature. Other nonlinear impairments have been evaluated in less than 10% of the literature. In short, linear impairments are more popular than non-linear impairments because of the simplicity of integrating linear impairments in RWA. Other nonlinear impairments such as Stimulated

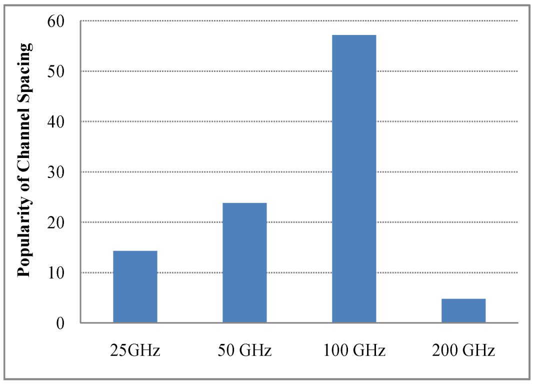

Fig. 4. Popularity of channel spacing in literature

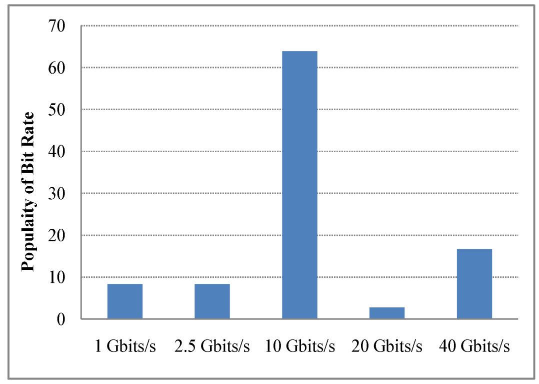

Fig. 5. Popularity of service bit rate in literature

Brillouin Scattering (SBS) [35] have never been evaluated within RWA setup.

Popularity of QoT Metric/Modulation Format/Bit Rate/Channel Spacing: Fig. 3 shows the percentage of QoT metrics utilized in literature to accept or reject a light-path. As it can be seen, BER is the most popular QoT metric (almost 34%) followed by OSNR (almost 24%). At the third and fourth ranks, Q-factor and crosstalk metrics are evaluated to admit a light-path. It is interesting to note that Q-factor metric is mostly used for integrated QoT-RWA schemes. Power level and EL metrics are less populated (less than 8%) than others to admit a candidate light-path. Now, the popularity of modulation format/bit rate/channel spacing is discussed, where the information stated in the following is based on the available data gathered from literature. Among all works that have stated modulation format, almost all of them have considered OOK modulation format, except [71], [73], [99] that has taken ODB modulation into account, and [99] that has considered RZDQPSK modulation. This is because most analytical models have been designed to 10 Gb/s NRZ-OOK channels [4]. According to Fig. 4, 100 GHz channel spacing is the most popular one followed by 50 GHz, 25 GHz, and 200 GHz. The popularity of 100 GHz channel spacing is because of avoiding impairments such as XPM and FWM that occur at smaller channel spacing. On the other hand, almost 63% of literature are interested in bit rate of 10 Gb/s (see Fig. 5), followed by 40 Gb/s, 2.5 Gb/s, 1 Gb/s, and 20 Gb/s. The popularity of 10 Gb/s could be due to the fact that some impairment such as PMD and accumulated CD become considerable at data rates higher than 10 Gb/s.

VII. Conclusions and Future Research

A comprehensive review of dynamic QoT-aware RWA techniques in transparent optical networks has been presented in this article. The characteristics of dynamic RWA techniques that consider physical layer impairments in all-optical networks have been reviewed. Two major categories of QoT-aware RWA algorithms have been detailed, where each category has been divided into two sub-categories of direct and indirect modelling of impairments. In direct modelling, the impairment model is directly incorporated in the RWA operation. In indirect modelling, a network parameter that has a correlation with impairment is integrated in the RWA process. At the end, a comprehensive discussion has been provided to compare QoT-aware RWA techniques based on different network and physical layer parameters.

This research area is still relatively young, and new techniques should be designed in future. The research direction should go toward the integration of QoT and RWA in order to simplify RWA. However, the big problem is how to map all the physical layer impairments into a single cost function since most of the impairments dynamically change in time or at the occurrence of an event (say the light-path establishment or termination). Moreover, no technique has considered wavelength conversion in the modelling of physical impairments. Furthermore, most of the techniques only consider the quality of a new light-path being setup. However, the establishment of a new light-path may degrade the quality of existing light-paths in the network. In addition, the connection requests for long distances experience a higher blocking rate than the connection requests for short distances.

According to the review provided in this article, the following list is proposed as the research directions in future:

1) Considering all the physical layer impairments in RWA: no work has considered all the physical layer impairments in RWA. Since the computational complexity of this issue could be very high, many researchers have considered a number of impairments that have dominant effects on light-paths. In an ideal RWA, however, all the impairments must be considered.
2) Involving wavelength converters in RWA: most of the works use optical switches without all-optical wavelength conversion, whereas all-optical wavelength converters can significantly reduce wavelength blocking probability.
3) Simplifying the computations required for modelling physical layer impairments in RWA: the calculations used for modelling the impairments are time-consuming. This reduces the network capability to find a suitable light-path in an online manner.
4) Rerouting: established light-paths can be rerouted in such a way that the BER of light-paths in the network becomes balanced.
5) Fairness of light-path setups among different connection requests so that the connection requests for long paths encounter almost the same blocking rate as the connection requests for short paths.

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