Fair QoS-Aware Adaptive Routing and Wavelength Assignment in All-Optical Networks

Yvan Pointurier, Maïté Brandt-Pearce
Charles L. Brown Department of
Electrical and Computer Engineering
University of Virginia, Charlottesville, Virginia 22904
Email: {yvan,mb-p}@virginia.edu

Tao Deng, Suresh Subramaniam
Department of Electrical and
Computer Engineering
George Washington University, Washington, DC 20052
Email: {tdeng,suresh}@gwu.edu

***Abstract*— In all-optical networks with no wavelength conversion, signals must travel on the same wavelength over possibly very long distances. During transmission, the QoS of signals as measured by their Bit Error Rates is degraded not only by the propagation through fibers, but also by small optical leaks from other signals called crosstalk that occur in the nodes and cannot be removed at the physical layer. We present a set of Routing and Wavelength Assignment algorithms that mitigate the crosstalk effects on all-optical network operation. These algorithms incorporate QoS information at both the routing and the wavelength assignment steps and account for dynamic crosstalk to yield better performance in terms of average BER and fairness among network users without sacrificing blocking probabilities, as shown through simulation.**

I. Introduction

All-optical networks are a new generation of optical networks in which nodes (the Optical Crossconnects, or OXC) switch signals in the optical domain, hence removing the electro-optical conversions which are a bottleneck in current optical networks. In all-optical networks, since signals are not regenerated[1],optical leaks called *crosstalk* propagate and accumulate over all-optical paths which can be several hundreds or thousands of kilometers long and thereby potentially causing sharp degradation in the network performance [1], [2]. Mitigating the effects of crosstalk in all-optical networks is a task that is difficult to do at the physical layer because crosstalk is in the same band as legitimate signals and therefore cannot be filtered out. Nevertheless, by selecting appropriate routes and wavelengths (with a carefully designed Routing and Wavelength Assignment, or RWA, algorithm) used by calls in the network at call arrival time, it is possible to minimize the occurrence and hence the impact of crosstalk in the network. More generally, it is possible, at the network layer, using a Quality of Service (QoS) aware RWA, to optimize the QoS of a network as measured by the Bit Error Rate (BER).

In QoS-constrained all-optical networks with no wavelength conversion, calls can be blocked either because there is no wavelength which satisfies the *wavelength continuity constraint* between the source and destination, or because a route that meets a *QoS constraint* (e.g., minimum BER) cannot be found. Because both crosstalk and wavelength availability depend on the network status, it is important that such RWA algorithms consider only those routes that can meet the wavelength continuity constraint, and that dynamically account for QoS at route establishment time. Such RWA algorithms are said to be adaptive [3], as opposed to classical RWA algorithms where routing is fixed during the network operation and a wavelength is then chosen to try to accommodate arriving calls [4]. In this work, we present adaptive RWA algorithms.

Traditionally, RWA algorithms in all-optical networks are evaluated using the *average call blocking probability* (BP) and the best RWA algorithms are those that minimize average blocking probability. Here, we are also interested in lowering average BER for the following reasons. First, BERs lower than the QoS threshold allow for higher network scalability and flexibility as adding links or inserting nodes on pre-existing links (and hence injecting additional crosstalk in the network) will only move the performance of the network closer to, rather than across, the QoS threshold. Similarly, robustness in the context of hardware aging is improved by operating far from the threshold. Finally, lower BERs imply fewer retransmissions at the higher layers and thus help increase the actual information data throughput.

Due to the wavelength continuity constraint, it is more difficult to establish a path between a source and a destination that are far away from one another in terms of hops. If we also account for noise and crosstalk impairments, establishing paths between distant sources and destinations is even more difficult because of the many sources of noise and crosstalk that may exist between the end nodes. Therefore, blocking probabilities (and BER) strongly depend on the end node pairs and call handling is not fair. Fairness has been quantified in the general context of circuit switched networks [5]; it is desirable to design *fair* RWA algorithms that try to accommodate both long, noise- and crosstalk-impaired paths, and short, low noise and crosstalk paths. It is also desirable to design RWA algorithms which are fair with respect to BER. Indeed, more reliable paths can forgo FEC (Forward Error Correction) techniques which can be used to relax the QoS (BER) constraint of a path [6], and since FEC is difficult to achieve at very high bitrates, FEC could be used and reserved for paths that exhibit high BER (because of length or high crosstalk for instance). The lower average and the fairest BER a RWA algorithm achieves,

[1]All-optical regeneration systems have been developed but deployment cannot be predicted in the near future as they are still at experimental stage.

the less FEC is needed and the more we can relax the BER threshold at the physical layer. In consequence, we evaluate our algorithms using average BP, BP fairness, average BER and BER fairness as metrics.

Although the RWA problem has been the topic of much research in the past, QoS-aware RWA in all-optical networks is only starting to get attention; QoS has been incorporated in RWA in [7] (Polarization Mode Dispersion (PMD) and amplifier noise impairments), [8] (PMD), [9], [10] (Four Wave Mixing), [11] (noise), [12] (PMD, residual dispersion and average nonlinear phase variation), [13] (electrical regeneration cost). In [14] and [15], many impairments including crosstalk are incorporated but the proposed RWA algorithms only include admission control procedures and do not incorporate QoS information in the RWA process.

In the past, we developed RWA techniques that include linear crosstalk impairments: separately at the routing step [16], and at the wavelength assignment step [17]. We also investigated QoS-aware adaptive RWA with a simplified model for crosstalk in [18], where only those paths that meet the wavelength continuity constraint were considered. In the present work, we study for the first time fairness issues with QoS-aware RWA algorithms. We propose two new *adaptive* RWA algorithms (called "highest Q factor", HQ, and "max min Q factor", MMQ) that account for the network status both in terms of existing connections and current *QoS* at both the routing and the wavelength assignment steps; the Q factor is directly related to the BER by $BER = 0.5\ \mathrm{erfc}(Q/\sqrt{2})$ using a Gaussian assumption [6]. Finally, we show that our RWA algorithms are more *fair* than their traditional counterparts where QoS information is used only to check if a tentative route meets a threshold (shortest path, "SP", and "SP2" which is a fairness-enhanced version of "SP").

This paper is organized as follows. In Section II, we describe the system of interest; we introduce our new QoS-aware RWA algorithms in Section III and evaluate them in Section IV. We draw brief conclusions in Section V.

II. System description

In this section, we present our model and assumptions for the network and crosstalk and introduce the metrics by which our new RWA algorithms are evaluated.

We consider a network of bidirectional links, each carrying the same number C of wavelengths in each direction. We assume that wavelength conversion is not available and thus a call must use the same wavelength from source to destination. Calls are assumed to arrive in the network according to a Poisson process with average arrival rate $load$ and call durations follow an exponential distribution with unit mean, such that $load$ is the total offered load of the network in Erlang. The sources and destinations of the calls are uniformly distributed over the set of nodes.

Crosstalk can originate from two components in the OXCs: the switching fabric (fabric crosstalk), and the demultiplexing stage (port crosstalk). Furthermore, crosstalk power due to demultiplexing leaks is channel-dependent: crosstalk is

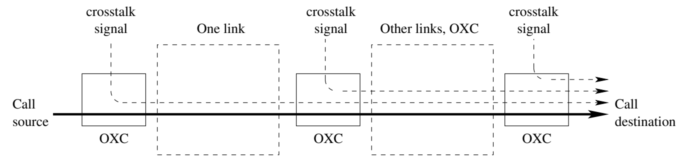

Fig. 1. Model of a transmission path used to compute the Q factor. Each OXC can inject one or more crosstalk components.

more powerful between two adjacent channels (adjacent port crosstalk) than between channels separated by one or more channels (non adjacent port crosstalk) since a demultiplexer is essentially a passband filter. From these two sources of crosstalk, we define three different types of crosstalk: co-wavelength, self, and neighbor-port crosstalk [17]. This is the model we use in this work.

A path in the network is shown in Fig. 1. Links are separated by OXC which inject crosstalk in the transmission path; each link is in turn made up of one or more fiber spans separated by amplifiers which inject (Amplifier Spontaneous Emission – ASE) noise in the path, as described in [19]. We model the transmission of crosstalk-impaired signals in an all-optical path and compute the Q factor of a path using the technique we developed in [19]. This fast, semi-analytical technique accounts for linear and non-linear propagation of both signal and crosstalk components, and amplifier noise. This work focuses on OXC crosstalk effects; therefore, interchannel nonlinearity, PMD, and insertion losses of components, which could be incorporated using models available in the literature, are not accounted for here. Let μ_0, μ_1, σ_0, σ_1 be the means and standard deviations for the 0 and 1 samples after reception at the end of a path; we can further split the variance σ_1^2 into ISI (Inter Symbol Interference – main signal linear and nonlinear propagation effects), ASE noise and crosstalk variances σ_i^2, σ_n^2, and σ_x^2, respectively. Then, the Q factor can be written as:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sigma_1} = \frac{\mu_1 - \mu_0}{\sigma_0 + \sqrt{\sigma_i^2 + \sigma_n^2 + \sigma_x^2}} \tag{1}$$

When a path is established or torn down, the Q factors for paths that share one or more OXC may change and be updated. Since crosstalk is modelled as a noise variance term in the Q factor and variances are additive, it is easy to account for crosstalk when a new call arrives as follows:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_0 + \sqrt{\sigma_i^2 + \sigma_n^2 + \sum_k {\sigma_x}_k^2}} \tag{2}$$

where the sum is dynamically updated during the network operation to include all crosstalk terms injected by the OXCs on the considered path at that instant.

As mentioned in Section I, we evaluate our algorithms for average blocking probability and BER. We are also interested in fairness, so that all calls have appropriate access to the network. We are using Jain's fairness index f_X, which is, for a resource X shared among *users*, a number between 0 and 1 where a fairness of 1 means that a resource is equally shared between all the users [5]. Formally, the fairness index is defined as:

$$f = \frac{E_{users}[X]^2}{E_{users}[X^2]}. \tag{3}$$

In this paper, the resource can be blocking probability or BER, and, denoting by $\mathbb{S}$ the set of possible $(source, destination)$ pairs, the "users" are the elements of $\mathbb{S}$. We therefore define a blocking probability fairness f_{BP}, and a BER fairness f_{BER}, as:

$$f_{BP} = \frac{E_{\mathbb{S}}[BP]^2}{E_{\mathbb{S}}[BP^2]} \text{ and } f_{BER} = \frac{E_{\mathbb{S}}[BER]^2}{E_{\mathbb{S}}[BER^2]}. \tag{4}$$

Given these metrics, desirable properties for QoS-aware RWA algorithms are: minimizing average blocking probability and BER, and maximizing blocking probability fairness and BER fairness. In the following section, we present new QoS-aware RWA algorithms that perform well for the aforementioned metrics.

Algorithm 1 Generic QoS-aware adaptive RWA

1: **for** i=1 … C **do**
2: Determine altered network topology considering only links where λ_i is free
3: Determine SP(λ_i) in the altered network topology
4: **if** Q factors for all lightpaths (including the tentative lightpath) are above threshold **then**
5: Mark SP(λ_i) as usable
6: **end if**
7: **end for**
8: Among the usable lightpaths, select one according to a predefined policy (SP, SP2, HQ, MMQ)
9: **return** selected lightpath

III. QoS-aware Adaptive Routing and Wavelength Assignment

Adaptive routing and wavelength assignment broadly refers to techniques where the choice of a route depends on the network state, as opposed to non-adaptive schemes where routing is fixed [3]. Traditionally, this means that a wavelength is chosen first according to some predefined policy, and a shortest route is computed in a modified topology which contains only the links from the original topology where the considered wavelength is available. This ensures that only paths that comply with the wavelength continuity constraint are considered.

In this work, we not only consider the topological state of the network at the routing time, but we also incorporate QoS information. We present four QoS-aware adaptive RWA algorithms; this set of algorithms is formally described in Algorithm 1. On a call arrival, we consider in turn each wavelength and remove links of the network where that wavelength is in use and compute the (physically) shortest route between the source and destination. If that route exists, we check that the QoS constraint (i.e., the Q factor) for all affected calls in the network, including that of the tentative call, would be respected if the call was established using the tentative route and wavelength. Once each wavelength has been considered, we pick a lightpath (route and wavelength) among at most C possibilities according to one of the following policies (cf. Algorithm 1, line 8):
• **SP** (Shortest Path) policy: pick the shortest path, in terms of physical distance. This is the standard, reference algorithm;
• the **SP2** policy implements a fairness-enhanced SP policy where calls can be established on short (single hop) paths only if 2 wavelengths or more are available to make it easier to establish longer paths than very short paths. This is a standard circuit switching networks idea which was presented in [20];
• **HQ** (Highest Q factor): choose the path with the highest Q factor; maximizing Q mitigates the insertion of new crosstalk when establishing a path, but can result in choosing a path longer that the shortest path, hereby wasting physical resources;
• **MMQ** (Max Min Q factor): choose the path that maximizes the minimum Q factor among paths affected by the establishment of the call. If a call is established, it injects crosstalk and modifies the Q factor for all paths used by previously established calls it crosses in the network, which conversely inject crosstalk on the considered path; the MMQ policy retains the path that will yield the maximum (among all possible wavelengths) minimum (among all paths crossed by the tentative path, including itself) Q factor. The MMQ policy tries to spread the crosstalk over the network such that all established paths are as far away from the QoS threshold as possible. Again, this policy may lead to waste of physical resources as non-shortest paths may be chosen.

Since the only difference between our new algorithms and the reference SP algorithm lies in choosing a wavelength at line 8 in Algorithm 1, our algorithms are as complex as the reference algorithm, yet much less complex than performing a global optimization over the whole set of possible lightpaths, an NP-complete problem [4].

The SP and SP2 adaptive-QoS aware algorithm are similar to the EXHAUSTIVE variant of the adaptive RWA presented in [3] where QoS conditions are enforced, such that the Q factor of any path, at any time, is above a fixed threshold. The HQ and MMQ adaptive-QoS aware RWA are new algorithms where QoS information is used actively to choose what route and wavelength will be used and were designed to perform well for QoS-related metrics. In the following section, we evaluate these HQ and MMQ algorithms against the SP and SP2 algorithms taken as references, for the metrics introduced in Section II.

IV. Simulations and results

We evaluated our QoS-aware adaptive RWA algorithms on the NSF topology depicted in Fig. 2, with C=8 wavelengths per link in each direction. The physical parameters used in the simulations are found in Table I; these are standard parameters for a regional area network. We enforced, as the QoS constraint, that any call, at any time, should use a path with a Q factor at least equal to $Q = 6$, which corresponds to a BER of 10^{-9}. For simplification purpose, we assumed that

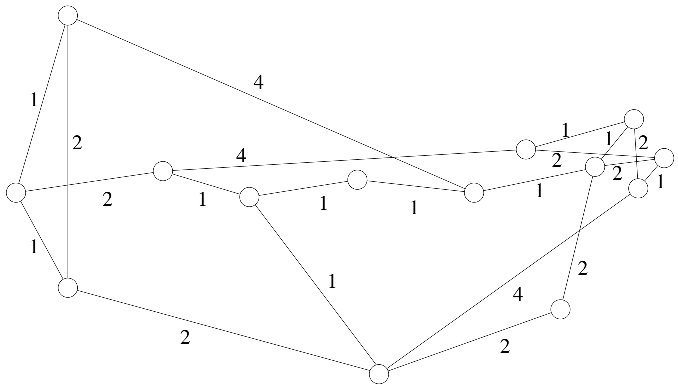

Fig. 2. **Topology used in the simulations.** We used a downscaled version of the NFS net topology (14 nodes, 21 bidirectional links) to perform our simulations. The link weights on the figure correspond to the number of fiber spans. Each span is 70 km long.

TABLE I
PHYSICAL PARAMETERS FOR THE SIMULATED NETWORK.

Description	**Value**
Span length	70 km
Signal peak power	2 mW
Bit duration	100 ps (10 Gbps)
Pulse shape	NRZ
Fabric crosstalk	−40 dB
Adj. port crosstalk	−30 dB
Non adj. port crosstalk	−60 dB
Fiber loss	0.2 dB/km
Nonlinear coefficient	2.2 (W km)$^{-1}$
Linear dispersion	17 ps/nm/km
Dispersion compensation	100% post-DC
Noise factor	2
Receiver electrical bandwidth	7 GHz
Number of wavelengths (C)	8
Minimum Q factor	6

all links were made of one or more 70 km long spans, and we scaled down the NSF topology so that every node is reachable from any other node. Indeed, due to physical transmission impairments and the absence of regenerating device in all-optical networks with no wavelength conversion, the maximum distance that can be covered by a signal is only 12 spans (less than 1000 km)[2]. This assumes the absence of crosstalk in the network; if crosstalk is present, the maximum transmission distance decreases. In Table II, we give maximum transmission distances over a path such that a Q factor of at least $Q = 6$ is maintained in the case where -30 dB crosstalk is injected at the beginning of the path. The first row is the number of (-30 dB) crosstalk components, all considered equivalent, assumed to be injected at the beginning of a transmission path, the second row is the maximum number of spans of the path before the Q factor drops below threshold. The impact

[2]Note that link distances longer than 12 spans are achievable using optimized long-haul link design and components.

TABLE II
IMPACT OF CROSSTALK ACCUMULATION ON THE MAXIMUM TRANSMISSION DISTANCE.

Crosstalk	0, 1	2, 3	4	5, 6	7, 8	9	10
Spans	12	11	10	9	8	7	6

TABLE III
FAIRNESS IN TERMS OF BLOCKING PROBABILITY.

Load	50	55	60	65	70	75
SP	0.15	0.25	0.29	0.36	0.43	0.50
SP2	0.19	0.27	0.28	0.37	0.50	0.54
HQ	0.17	0.25	0.28	0.37	0.45	0.51
MMQ	0.17	0.31	0.35	0.40	0.48	0.53

TABLE IV
FAIRNESS IN TERMS OF BER.

Load	50	55	60	65	70	75
SP	0.24	0.28	0.30	0.32	0.37	0.35
SP2	0.27	0.32	0.32	0.35	0.38	0.40
HQ	0.22	0.28	0.24	0.31	0.37	0.35
MMQ	0.34	0.42	0.39	0.43	0.43	0.45

of crosstalk on maximum transmission distance is clear: with only 10 crosstalk sources, the maximum distance is half of that of the no-crosstalk case.

The average blocking probabilities for various network loads and for each of our QoS-aware adaptive RWA algorithms are presented in Fig. 3. The HQ algorithm performs slightly better as measured by blocking probability than the traditional SP and than MMQ. The SP2 algorithm performs worse which is expected given that it is designed with fairness only in mind, but overall the performance of all RWA algorithms are in the same order of magnitude. The reason why HQ and MMQ do not perform necessarily better than SP is twofold. First, although HQ and MMQ tend to minimize crosstalk in the network, they tend to choose longer paths hence wasting resources. Second, because the crosstalk injected in the OXCs is higher when it originates from adjacent channels than from non-adjacent channels, HQ and MMQ tend to spread the calls among the wavelength spectrum similarly to the traditional LU (least used) scheme [4]. Although such a wavelength spreading behavior tends by construction to reduce crosstalk in the network, it also increases the blocking probability as was shown in in the context of non-QoS aware RWA. Overall, the trade-offs translate into a slightly lower blocking probability for HQ and a slightly higher blocking probability for MMQ, compared with SP.

In Fig. 4, we report average BER for the tested RWA algorithms at different loads. Here, HQ performs several times better than the other RWA policies, while SP/SP2 perform poorly especially at lower loads. This is expected given that HQ and MMQ try to maximize the QoS in the network (that is, minimize the BER), while SP/SP2 only enforce that a minimum QoS is met.

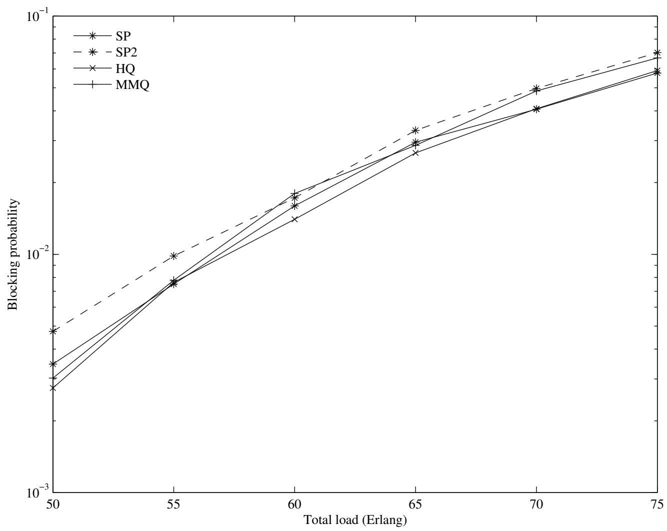

Fig. 3. Average call blocking probability for the four QoS-aware adaptive RWA algorithms.

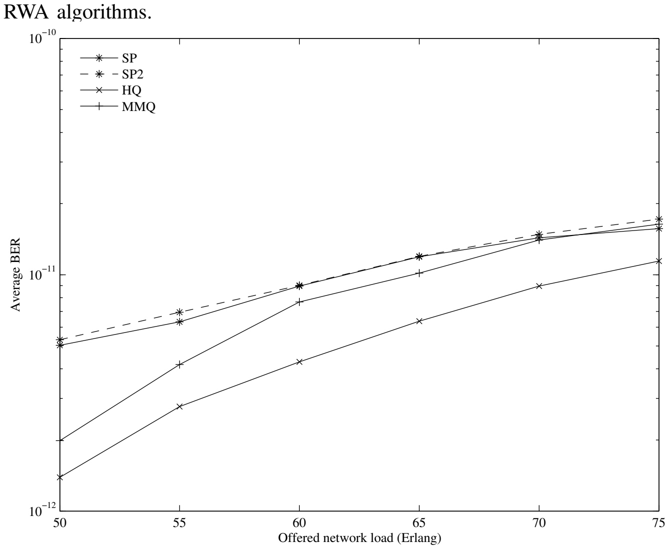

Fig. 4. Average call bit error rate for the four QoS-aware adaptive RWA algorithms.

Finally, we report fairness indices for both blocking probability and BER in Tables III and IV, respectively; MMQ is the fairest policy in terms of both blocking probability and QoS (bit error rate), while HQ and SP exhibit equivalent performance. Note that MMQ is superior to the other algorithms in terms of fairness, even compared to previously proposed fair techniques (SP2). We additionally report the histograms for BER over the set of possible (source, destination) pairs for an offered network load of 55 Erlangs in Fig. 5; this histogram offers a graphical interpretation of the BER average and fairness, since fairness is directly related to distribution variance as can be seen in (3). It is apparent that the BERs for paths set up with MMQ are less spread, compared with SP, SP2 and HQ. Moreover, more paths with HQ and MMQ are further away from the QoS threshold, which is desirable for robustness and scalability as mentioned earlier.

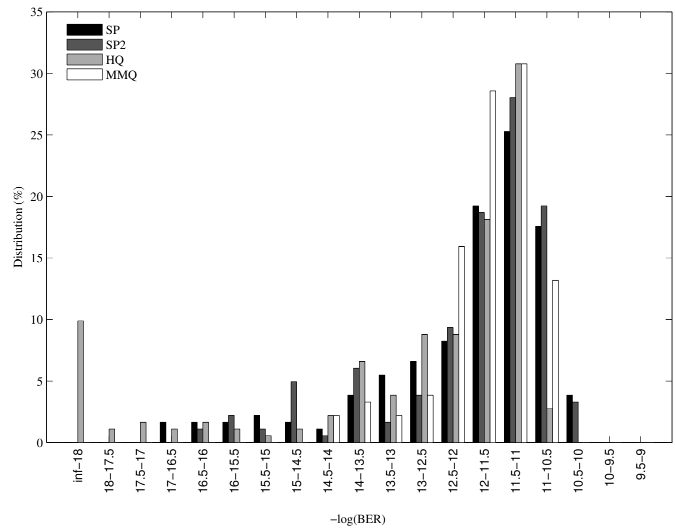

Fig. 5. Distribution of the BER taken as a random variable of the (source, destination) pairs for a load of 60 Erlangs.

V. Conclusion

The RWA algorithms we presented in this work exhibit desirable properties for optical network operation, namely, low BER, and high fairness for both blocking probability and BER. This was achieved by making the choice of the route and the wavelength dependent on both the wavelength occupation in the network, as well as crosstalk information, in order to minimize crosstalk impairment and maximize QoS measured in terms of BER. The algorithms we presented differ in the policy (called SP, SP2, HQ and MMQ) used to choose the route among a limited number of possible choices. Our new algorithms HQ and MMQ were compared to QoS-aware versions of standard algorithms (SP and SP2). The QoS performance of the new algorithms were investigated and shown to be superior to that of the standard algorithms without sacrificing blocking probability. Which of our RWA algorithms should be chosen when deploying a network depends on what metric has to be optimized; as a rule of thumb, HQ tends to optimize blocking probability and BER averages while MMQ tends to optimize fairness.

Our new algorithms improve QoS in crosstalk and noise impaired all-optical networks, however they perform only as good as the reference algorithms in terms of blocking probabilities. As a future task, we plan on lowering call blocking probabilities with QoS-aware algorithms by trading the high performance in terms of QoS against lower blocking probabilities. To do so, we envision hybrid RWA algorithms that can choose automatically which policy to use, depending on such factors as path length and how close the Q factor of a path is from the threshold.

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