Poster Paper

Dynamic Routing and Wavelength Assignment in Transparent WDM Networks with Amplifiers' Power Constraints

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Abstract: In a wavelength-routed optical network, the signal remains in the optical domain over the entire route (lightpath) from source to destination node. Thus, while propagating through the network, the signal quality may degrade as it encounters physical impairments. In this paper, we study the establishment of new connections in such a network in the presence of amplifier optical power constraints. In particular, a Multicost Impairment Aware Online RWA (IA-RWA) algorithm is extended to include amplifier power constraints. The extended algorithm accounts not only for the channel utilization in the network but also for the amplifiers' possible saturation, which change as new connections are established or released, in order to calculate the noise variances that correspond to physical impairments on the links. We find that when these effects are taken into account the two algorithms achieve similar performance when the amplifiers operate in the linear region. In the case, however, where the amplifiers are saturated, the extended algorithm exhibits better performance compared with the previously proposed algorithm, in terms of blocking probability and frequency of reroutings required.

Keywords: IA-RWA, amplifiers, power constraints.

1. Introduction

We consider transparent optical networks where, in response to a given call request, a circuit-switched connection is established between the source and the destination nodes on a single wavelength. Routing in such networks involves the identification of a path and a wavelength (jointly called a lightpath) between the source and destination nodes for each connection request. In a transparent wavelength-routed optical network, any transmitted signal remains in the optical domain over the entire route assigned to it.

Traditional Routing and Wavelength Assignment (RWA) algorithms find a lightpath that either minimize a certain cost parameter - such as the length of the connection or the network resources used - or maximize the traffic served. The RWA problem is usually considered over two alternative settings. Static or Offline lightpath establishment addresses the case where the set of connections is known in advance and are jointly served. Dynamic or Online lightpath establishment considers the case where connection requests arrive at random time instances and are served on a one-by-one basis. In this study we will focus on the Online RWA problem.

Most of the RWA algorithms assume an ideal physical layer transmission, [1]-[3]. However, in all-optical transparent network, where the signal may traverse a number of intermediate nodes and long fiber segments, the signal quality degrades due to physical

layer impairments which may make some routes infeasible (physical-layer blocking) [4], [5]. Hence, impairment-constraint-based routing is needed in order to ensure that the connections are feasible with acceptable Quality of Transmission (QoT).

To accomplish this, it is necessary to consider not only the physical performance of the connection but also the equally important network-level conditions. In [6], an adaptive IA-RWA algorithm that models as noise the most important physical impairments and assigns additive noise variance parameters per link is proposed. In [7] authors evaluate the network performance while capturing the most significant physical layer limitations involved in the BER estimation. The existence of other calls currently in progress, i.e., traffic variation, will affect the crosstalk, the wavelength dependence, saturation of gains and ASE noise generation and as a consequence the BER estimate.

Since optical signal detection at the receivers necessitates a certain power level that must not be less than a certain threshold, the RWA problem must take the optical signal power level into consideration. Some studies that address the signal power have been proposed [8], [10] using different amplifier gain equations but with the objective to minimize the blocking probability.

In this paper, we extend the Multicost Impairment-Aware Online Routing and Wavelength Assignment algorithm (IA-RWA) proposed in [9], so as to account for the power effects. The crosstalk and the ASE noise generated at every intermediate node propagate along with the signal over the assigned lightpath; and all of them undergo variable gains at various wavelengths because of the traffic-dependent, non flat gain spectra of Erbium-Doped Fiber Amplifiers' (EDFA) [13]. Our aim is to account for dependence between the amplifiers' gain and the number of wavelengths crossing an amplifier. More specifically, the gain that amplifies the transmission signal depends on the input power of the amplifiers. Consequently, we take into account, in the process of routing requests, the changes of the amplifiers' gain, which depends on the number of wavelengths an amplifier. The calculation of the exact value of the amplifiers' gain gives us better performance, with better blocking probability, fewer reroutings but larger execution time, compared to the IA-RWA algorithm proposed in [9].

The rest of the paper is organized as follows. Is Section 2, we introduce the network simulation model that is used with its components. In Section 3, we detail the Multicost Impairment RWA algorithm. In Section 4, we report our performance results and Section 5 concludes the paper.

2. Network Simulation Model

An all-optical network consists of the interconnection of optical cross-connect switches (OXC), by pairs of unidirectional fibers.

Fig. 1a shows a typical OXC consisting of three stages. In general, an OXC includes a cross connect switch (XCS), a pair of Erbium-Doped Fiber Amplifiers (EDFA) and optical power taps, on either side of the XCS at each port, for monitoring purposes. The EDFA on the input side (with small-signal gain, Gin) compensates exactly for the signal attenuation along the input fiber and the tap losses. The EDFA at the output side (with small-signal gain, Gout) compensates exactly for the losses at the cross connect switch (XCS) [7]. The optical signal that enters an OXC passes through various components that contribute to power loss/gain.

The link model typically utilized in a wavelength routed network is presented in Fig. 1b. For a fiber link between nodes on the lightpath inline amplification is employed. The link is divided to spans, which consist of a standard single-mode fiber (SSMF) segment, followed by a dispersion-compensated fiber (DCF) segment. The role of the DCF segment is to compensate the dispersion slope of the SSMF segment. At the end of each SMF span there is a double stage EDFA that is used to compensate the corresponding losses. Also, a DCF

fiber module exists at the intermediate stage of the EDFAs for the dispersion management. At the beginning of the link there is also a pre-compensating fiber module while post-compensation may also be provided at the end of the link.
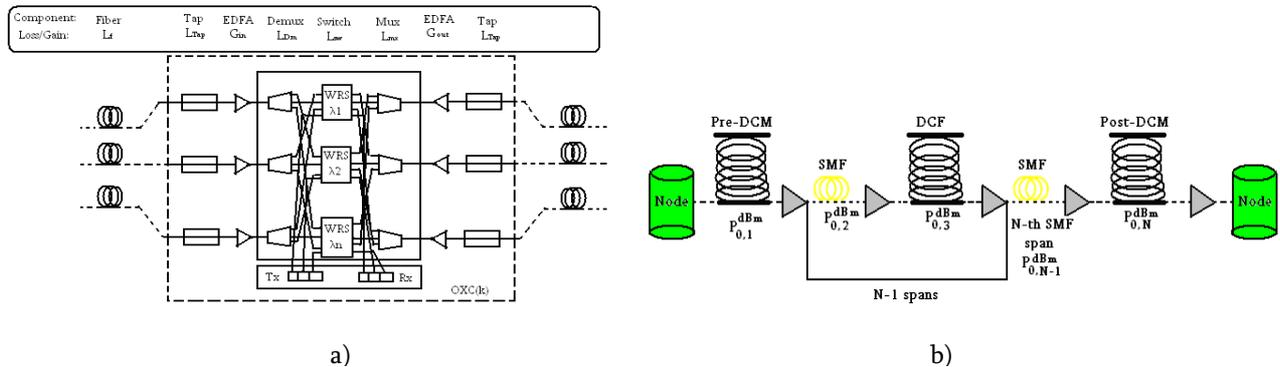
Figure 1: a) Components and their loss/gain parameters in a OXC [7], b) Link model

2.1 – Amplifier Gain

The EDFA gains for each node at all the wavelengths are evaluated using a simplified model that accounts for the main physical phenomena, such as multi-wavelength signal propagation and self-saturation of the EDFA gains by the traffic-dependent signal channels. EDFA amplifier gain measures the ratio of the output power of the signal to its input power and depends on the number of wavelengths in the input signal. The output power of the amplifier is limited due to pump power and amplifier design itself. An important feature of the EDFA amplifiers in WDM transparent networks is their ability to keep the characteristics constant when one or more input channels are added or dropped. As a result, when the input signal power is increased, the amplifier gain drops. To address this issue, various analytical models have been proposed in the literature like [8], [10]. For our study this behaviour is approximated as $G(P_{in}^{dBm}) = \min\{G_{Max}^{dB}, (P_{Sat}^{dBm} - P_{in}^{dBm})\}$ (1)

where P_{in}^{dBm} is the aggregate power of the input signal in dBm, and G_{Max}^{dB} is the small-signal gain in dB [10]. In particular, the aggregate power of all wavelengths on the fiber should not exceed an upper bound P_{Sat}^{dBm} which is the amplifier's internal saturation power (in dBm). This gain applies to all input wavelengths assuming flat gain over all the channels.

We must mention that for low input powers, the amplifier operate in linear region (G_{Max}^{dB}), and for very high input powers the gain limit to $G \rightarrow 1$ and then the output power is equal to the input power $P_{out} = P_{in}$, due to the fact that
$$Pout = Pin * G \qquad (2)$$
In the literature, equal gain is assumed for all connections (on different wavelengths) entering a specific amplifier regardless of their individual power levels. This is referred to as flat-gain with (linear) homogeneous broadening [15].

In order to calculate the amplifier gains in the network and account for those that work in the saturation region we use the following approach. Before establishing a new lightpath we assume that we are given the wavelength utilization of all the links of the network (i.e., the already established lightpaths). At each wavelength passing through a link we assign transmission power equal to P_0^{dBm}. We calculate the total power P_{in}^{dBm} of all wavelengths on the link and use Eq. (1) to see if the new connection would saturate the amplifier. The gain remains stable in the linear region of the amplifier, and starts to reduce when it enters the saturation region. Saturation occurs when the total input power of the amplifier exceeds a

given threshold and this means that the amplifier cannot work at its full capacity. When this situation occurs, the available gain for individual signals is no longer the small-signal gain (i.e., a reduction in gain occurs), but rather it is a decreasing function of the aggregate input power. Finally, according to this gain the output power of the amplifier is determined, the input power of the next amplifier, based on Eq. (2).

Note that the number of wavelengths that saturates the amplifier depend on the input power P_0^{dBm} of each wavelength. Even one individual connection with a high signal power might saturate the amplifier and reduce the gain for other signals sharing the same amplifier. In this study, however, we assume equal input power for all wavelengths.

2.2 – Amplifier Cascading

Consider that the receiver gets the signal over a link with cascading amplifiers, numbered as 0,1, …,N starting from the transmitter, as shown in Fig. 2 (the pre-amplifier can be considered as amplifier 0 in the cascade.) Let G_i be the amplifier gain and N_{spi} be its spontaneous emission factor. The span between amplifier i and i-1 has attenuation L_i.
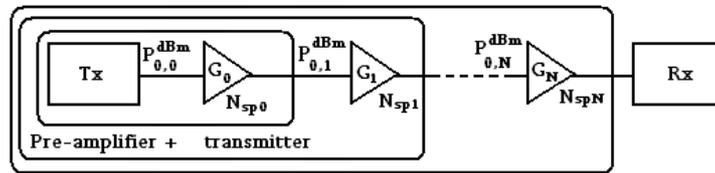
Figure 2: Cascading of amplifiers

An important assumption made here is that along the cascaded amplifiers when the gain goes to the saturation region for the first amplifier the rest of the inline amplifiers remain in their linear region. When the first inline amplifier is saturated the input power is higher than the saturation power,

$$P_{in}^{dBm} > P_{Sat}^{dBm} \Rightarrow w * P_{0,1}^{dBm} * L_{\mathrm{Pr}e-DCM}^{dBm} > \frac{P_{Sat,out}^{dBm}}{G_{Max}^{dB}}$$ and the output power is $P_{Sat,out}^{dBm} = P_{Sat}^{dBm} * G_{Max}^{dB}$,

where w is the number of occupied wavelengths, $P_{0,1}^{dBm}$ is the input power for each wavelength, $L_{\mathrm{Pr}e-DCM}^{dBm}$ is the loss for the Pre-DCM fiber, $P_{Sat,out}^{dBm}$ is the output power when the amplifier is saturated and G_{Max}^{dB} is the maximum output amplifier gain . Then the second amplifier is in the linear region, since $L_{SMF}^{dBm} * P_{Sat,out}^{dBm} < \frac{P_{Sat,out}^{dBm}}{G_{Max}^{dB}} \Rightarrow L_{SMF}^{dBm} * G_{Max}^{dB} < 1$.

As the second amplifier is not saturated, its output power is unable to saturate the third amplifier and this continues until the last amplifier of the cascade.

2.3 – Physical Impairments

Physical layer impairments (PLIs) are usually categorized to linear [12] and non-linear [11], according to their dependence on the power. However, when we consider IA-RWA algorithms it is useful to categorize the PLIs to those that affect the same lightpath, [Amplified Spontaneous Emission noise (ASE), Polarization Mode Dispersion (PMD), Chromatic Dispersion (CD), Filter concatenation (FC), Self-Phase Modulation (SPM)] and to those that are generated by the interference among lightpaths, [Crosstalk (XT) (intra-channel and inter-channel crosstalk), Cross-Phase Modulation (XPM), Four Wave Mixing (FWM)].

3. Multicost Impairment Aware Online RWA with Amplifiers' Power Constraints

To serve a connection, the proposed algorithm finds a path and a free wavelength that has acceptable QoT performance by estimating the corresponding Q-factor. We account for the current utilization of the network and the changes in the amplifiers' gains as the number of the lightpaths crossing them, changes with the establishment or release of new connections, in order to calculate the noise variances of the links. These, along with the time invariant eye impairment penalties of all candidate paths, form the inputs to the algorithm.

Assuming that the network supports m wavelengths, the multicost algorithm uses the utilization state of the network in order to calculate a cost vector per link l that has $3+3 \cdot m$ cost parameters, $V_l = (d_l, \overline{W_l}, \overline{\sigma^2_{1',l}}, \overline{\sigma^2_{0',l}}, G_l, P_l)$, where $\overline{W_l}, \overline{\sigma^2_{1',l}}, \overline{\sigma^2_{0',l}}$, are cost vectors of size m, that map utilization per wavelength, the noise variance of bit 1, and noise variance of bit 0, while d_l, G_l, and P_l are the delay (or length), the gain in dB that is computed as identified in equation 1 and the power of link l, respectively.

Similarly to a link, a path has a cost vector with $3+3 \cdot m$ cost parameters, in addition to the list of labels of the links that comprise the path. The cost vector of p can be calculated by the cost vectors of the links $l=1,2,..,n$, that comprise it as follows:

$$V_p = \left(\sum_{l=1}^{k} d_l, \underset{l=1}{\overset{k}{\&}} \overline{W_l}, \sum_{l=1}^{k} \left(\overline{\sigma^2_{1',l}} * \prod_{i=l+1}^{k} 10^{2*G_i/10} \right), \sum_{l=1}^{k} \left(\overline{\sigma^2_{0',l}} * \prod_{i=l+1}^{k} 10^{2*G_i/10} \right), \sum_{l=1}^{k} G_l, \sum_{l=1}^{k} P_l \right)$$

The proposed multicost algorithm consists of two phases. Before entering the first phase the cost parameters are initialized, calculating the amplifiers gain and the noise variances so as to create the cost vectors. In the first phase, the algorithm finds the set of so called non-dominated Q paths from the given source to all the nodes of the network, including the given destination. This can be viewed as a generalization of Dijkstra's algorithm that only considers scalar link costs. The basic difference is that instead of a single path, a set of non-dominated paths between the origin and each node is obtained. A path that is dominated by another path, has worse delay (or length), wavelength availability, and QoT than the other path, and there is no reason to consider it or extend it further. During the calculation of the non-dominated paths when we expand a path we check the Q-factor of its wavelengths and we drop the path if it is not further extendable. In this way in the end the non-dominated paths that the algorithm returns have at least one available wavelength. Moreover, the paths and available wavelengths have at least acceptable Q-factor performance, since lightpaths with unacceptable Q-factor were made unavailable in the process of the algorithm. In the second phase, an optimization function is applied to the cost vector of the paths, in order to find the optimum solution. Various objective functions are proposed and evaluated in order to choose the optimal lightpath to serve the connection. Finally, when a lightpath is established, to continue with the procedure of the reroutings, the amplifiers gain must be checked again for variations because the QoT of some already established lightpaths may become unacceptable, and the corresponding connections will have to be rerouted.

4. Performance Results

In order to evaluate the performance of the proposed IA-RWA with power constraints algorithm we carried out a number of simulation experiments in Matlab. The simulation experiments were performed assuming the DT network topology (Fig. 3a), which is a transparent candidate network, as identified by the DICONET project [14].

To evaluate the feasibility of the lightpaths we use a Q-factor estimator tool that calculates the Q-factors of the new and the already established lightpaths and determines those with unacceptable transmission quality. The choice of the optimum lightpath is made using the best Q policy (bQ) policy. The link model has been already presented in Section 2

in Fig. 1b. We assumed 5000 connections, and 100GHz channel spacing. The span length in each link was 100km. Each link was assumed to consist exclusively of SSMF fibers with dispersion parameter D = 17ps/nm/km and attenuation parameter a = 0.25db/km. For the DCF we assumed a= 0.5dB/km and D=-80ps/nm/km. The launch power was 3dBm/ch for every SMF span and -4dBm/ch for the DCF modules.

a)   b)
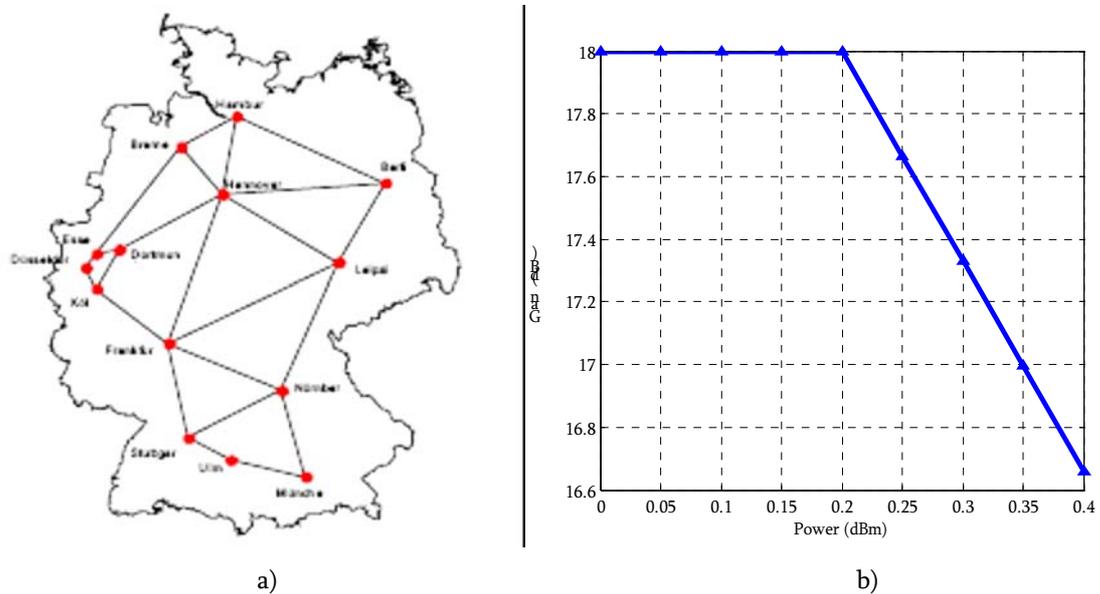
Figure 3: a) DT network (14 nodes and 23 links) , b) Calculated gain saturation curve for input power variation

The EDFAs' noise figure was 6dB with small variations ($\pm$0.5dB) and each EDFA exactly compensates for the losses of the preceding fiber span. We assumed a switch architecture similar to and a switch-crosstalk ratio Xsw = 32dBs with small variations per node ($\pm$1dB). Regarding the dispersion management scheme, a pre-compensation module was used to achieve better transmission reach: every span was under-compensated by a value of 30ps/nm to alleviate non-linear effects, and the accumulated dispersion at each switch input was fully compensated to zero using an appropriate post-compensation module at the end of the link.

The source and destination of a connection are uniformly chosen among the network nodes. Connection requests, with requesting bandwidth equal to 20Gbps, are generated according to a Poisson process with rate λ=1 connection/time unit. The duration of a connection is given by an exponential random variable with average 1/μ=100 time unit.

An important feature of the EDFA amplifier in its use in WDM transparent networks is its ability to keep the characteristics constant when one or more input channels are added or dropped. As a result, when the input signal power is increased, the amplifier gain drops, as the example in Fig. 3b.

Fig. 4 presents a comparison of the blocking probability between the original IA-RWA algorithm and its extension with power constraints (IA-RWA with power constraints). The blocking probability decreases rapidly at the beginning and more smoothly later on, as the number of available wavelengths increases.

It is shown that for less than 35 available wavelengths the two algorithms have the same performance, but when the number of available wavelengths exceeds 35 the IA-RWA with power constraints is improved and performs better blocking probability. This is explained due to the fact that the amplifier goes to the saturation region ($G(P_{in}^{dBm}) > G(P_{out}^{dBm})$), or

according to Eq. 1 $G_{Max}^{dB} < P_{Sat}^{dBm} - P_{in}^{dBm}$) when the number of wavelengths are more

than 35. If the input power changes and for example is increased to P_0^{dBm} = -2dBm the number of wavelengths that are able to saturate an amplifier drops to 22. Comparing Fig. 4a and Fig. 4b is obvious that reroutings help the algorithm to have better blocking probability and even if reroutings are not used IA-RWA with power constraints behaves better.

a)   b)
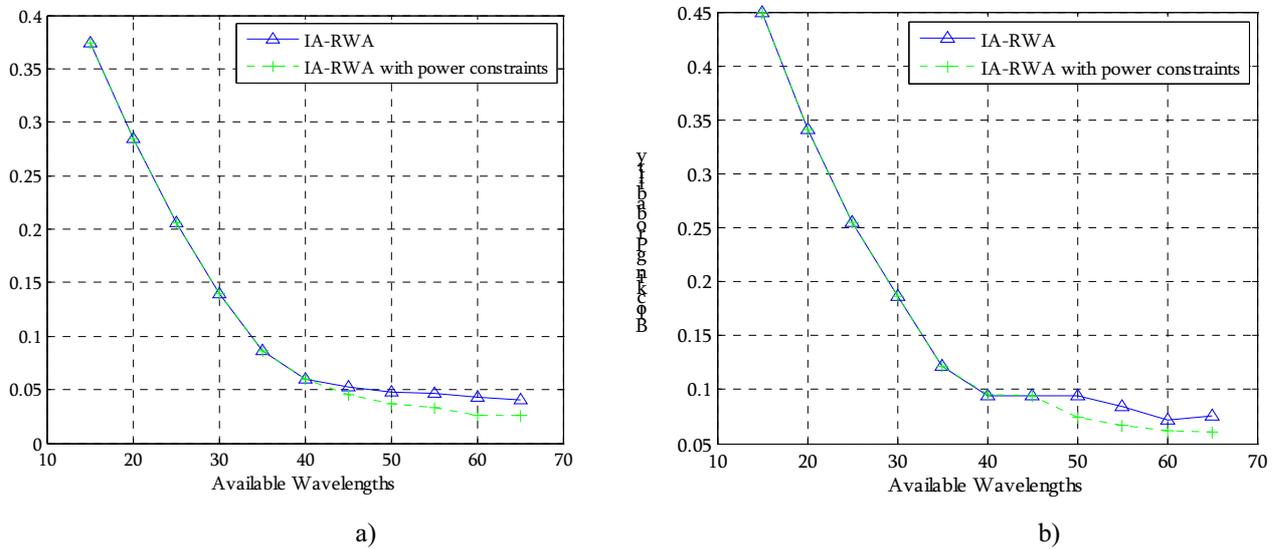
Figure 4: Blocking probability with the available wavelengths in the network, (a) with reroutings, (b) no reroutings (load=400).

For increasing load and reroutings activated, the two algorithms have similar performance, with IA-RWA with power constraints to perform slightly better. The similarity to the performance of the algorithms is explained by Fig. 5, where the number of reroutings for the IA-RWA is more than IA-RWA with power constraints. The increased number of reroutings improves the blocking probability metric, but this lead to interruption to the service of the connections.

IA-RWA with power constraints performs better in terms of the blocking and the rerouting probabilities, but requires more execution time. This increased execution time is expected since the algorithm calculates twice, at the beginning and at the end, the amplifiers' gain for all nodes in the network.

The number of reroutings for the IA-RWA with power constraints is relative small, and hence the execution time of the algorithm with reroutings and without reroutings is almost the same as can be seen in Fig. 5. Also, the two algorithms for the case of reroutings and 50 available wavelengths have similar execution times. This is because the IA-RWA algorithm performs many reroutings as can be seen in Fig. 5 (load =400), while IA-RWA with power constraints performs a smaller number of reroutings but needs more time to compute the gain of the amplifiers.

5. Conclusions

We presented an IA-RWA algorithm for serving online traffic while accounting for power constraints and calculating the exact value of the amplifiers' gains in evaluating the quality of transmission. The total output gain of the amplifier is saturated due to the increase of the input signal power which depends on the utilization of the wavelengths. Lower blocking probability for new connections and lower rerouting probability for already established connections is accomplished with the algorithm presented.
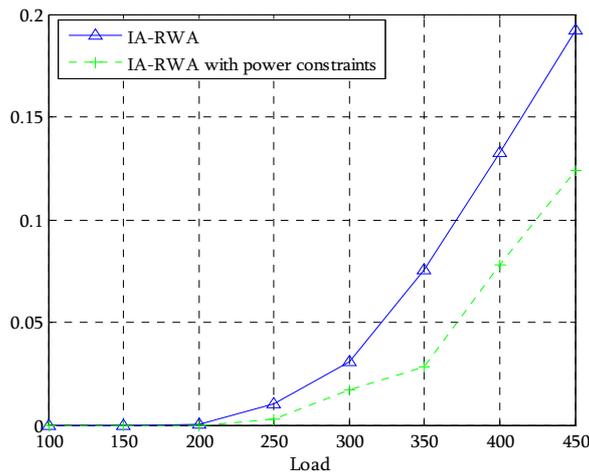
Algorithm	Average execution time per connection in seconds (load=400)			
	No reroutings		Reroutings	
	W=40	W=50	W=40	W=50
IA-RWA	0.727	0.911	0.771	1.332
IA-RWA with power constraints	0.952	1.283	0.976	1.355

Figure 5: Average number of reroutings versus traffic load and execution times

Acknowledgement

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