Evaluation of Wavelength Congestion in Transparent Optical Transport Networks

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***Abstract*— Transparent Optical networks are generally regarded as a possible solution for the provisioning of ultrahigh speed transmission and switching capabilities to accommodate bandwidth hungry applications and services. Most of such applications and services involve streaming of high-definition video. However, since al source and destination pair establishments within a given Transparent optical transport network are assumed to be within optical signal reach, such networks do not incorporate regenerators. The lack of regenerators often leads to a serious degradation of the signal to noise ratio as a result of the effects of physical layer impairments accumulated as it traverses the network. This motivates us to propose and present a Q-factor tool that takes into account the various physical layer impairments. The proposed tool's efficacy is evaluated by way of simulation.**

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Keywords*— *Transparent networks, Q-factor tool, wavelength congestion, blocking probability, path congestion, network congestion, physical impairments

I. INTRODUCTION

Transparent optical transport networks are generally regarded as a relatively cost-effective solution for ultra-high-speed transmission and switching network to accommodate bandwidth- intensive applications and service that characterize today's everyday life. The lack of repeaters makes such networks quite energy efficient as mot of the power is expended within these units. However, signals traversing such networks still suffer degradation due to the effects of physical layer impairments. So, the lack of repeaters means that the received signal may have been seriously compromised in quality thus leading to generally bad quality of service (QoS) overall. The presence of repeaters would otherwise mean refreshing of the signals whenever it is necessary. The effects of these physical impairments also limit on the number of simultaneous end-to-end lightpath connections that can be established, subject to the mandatory wavelength continuity. It may therefore be necessary to implement approaches that take care of these impairments as we establish connections in the network. The impairment aware routing and wavelength assignment (IA-RWA) approach would always thrive to avoid paths and links that otherwise are already susceptible to high levels of signal impairments. Common linear impairments that degrade optical signals in optical networks are:
polarization mode dispersion (PMD), chromatic dispersion (CD), fibre attenuation (FA), polarization dependant losses (PDL), crosstalk (XT), Filter Concatenation (FC), amplified spontaneous emission (ASE) and component insertion losses (CIL). A summary list of impairments is provided in Figure 1.

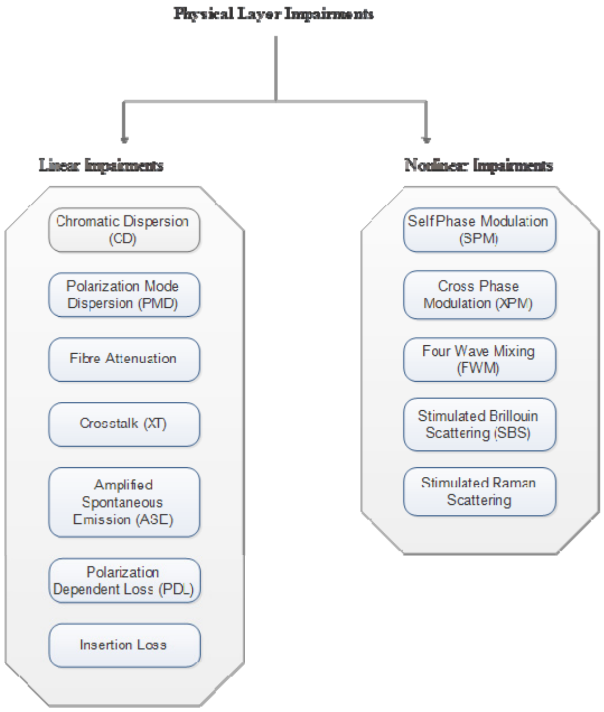

Fig. 1. Physical impairments.

We therefore need focus attention towards solving the IA-RWA problem so as to promote a consistent as well as acceptable quality of transmission (QoT) in Transparent Optical transport networks. Quite a few approaches in this regard have been explored in various literatures. They all are geared to catering for transmission impairments in network design and subsequent operation [1]. [2], [3]. They generally more or less follow the same procedural steps in dealing with the physical impairments. These include:

- the computing of possible paths and wavelengths and using existing RWA algorithms, and ultimately verifying the signal quality by considering the effects of physical layer impairments.
- the would be effects of physical layer impairments (PLIs) are taken into consideration during the RWA processes.
- Verification of the signal quality of the chosen candidate end-to-end lightpaths prior to actual dispatching of traffic.

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The work in [4] presents a shortest-path based RWA algorithm that attempts to find candidate primary and protection links subject to the end-to-end wavelength-continuity constraint being satisfied. The Q-factor of all candidate paths are computed, and the path that has the greatest Q-factor is ultimately chosen as the candidate for the establishment of the new connection request.

The work in [5], similarly propose and analyze *k*-SP based IA-RWA algorithms that cater for the most common impairments such as ASE, GVD and PMD. In the same work Q-factor penalties are enforced and at the same time utilized to compute the edge weights, instead of the actual lengths. A comparison is then made between on-line off-line and routing and subsequently it is generally noted that IA-RWA algorithms, and the on-line routing algorithms are more computationally intensive hence require more computational time as compared to their off-line counterparts. On the other hand, the on-line IA-RWA algorithms appear to offer significantly lower blocking probabilities by comparison. Both categories of algorithms have a common disadvantage of not taking into consideration all the key impairments and thus they may not be practical high capacity transport networks that operate at speeds in excess of 100 Gb/s.

An integer liner programming (ILP) formulation and heuristic approaches for candidate route computations is explored by way of initially calculating link costs derived from impairment effects of ASE and PMD [6]. XT is considered in the RWA decision making by the authors in [7]. A dynamic computation based adaptive routing algorithm is proposed and evaluated by the authors in [8]. It is then used to calculate Q-factor values obtained from active network devices.

Similarly, the authors in [9] propose and present a few algorithms that compute the *k*-SP by utilizing Q penalties as path costs. In this work, the decision on the establishment of a connection request will be based on the comparison between a preset IA threshold and computed Q-factor. In [10], the proposed algorithm selects a route by way of initially verifying the extent of signal degradation due to PLIs at each active network node.

II. PHYSICAL-LAYER IMPAIRMENTS MODEL

We commence the section by looking at two general models that ere proposed in [11] assist in the factoring in of the effects of PLIs in RWA algorithms. These models are: (i) analytical models, and (ii) hybrid models. With the earlier, the PLIs are computed by making use of closed-form formulae, whilst in the latter, both analytical models as well as simulation approaches are utilized in the evaluation of the physical layer's performance.

Among a host of available optical performance measuring attributes, the Q-factor is preferred as the most suitable metric to use for the routing algorithms as it has a robust correlation as well as resemblance with the BER [12], [13], [14].

The inter-relationship between BER and the Q-factor is best described by the following equation:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{1}$$

where,

$$Q = \left(\frac{\langle I_1\rangle - \langle I_o\rangle}{\sigma_1 + \sigma_2}\right) \tag{2}$$

$\langle I_1\rangle$ and $\langle I_{01}\rangle$ are the mean photocurrent values of high and low signal levels respectively.

σ_1 and σ_o are the standard deviations of high and low signal noise levels respectively.

The work in [15] reports the use of the quality of transmission (QoT) parameter in evaluating the signal health in impairment aware optical networks.

In this paper, we partly make reference to the findings in 16] to incorporate the effects of XT and FC noises. We further quantify the PLI effects by employing analytical models presented in [17], [18] and [19].

Thus, our proposed model includes the effects of the following physical impairments: ASE, CD, XT, PMD, FC, SPM, XPM and FWM. The proposed expression is given in the following equation:

$$Q_d = [EyePenalty] \times [NoisePenalty] \times Q_s \tag{3}$$

Q_d is the connection destination Q-factor value, Q_s is the connection source Q-factor value.

$$EyePenalty = \left(\frac{\langle I_1\rangle_d - \langle I_o\rangle_d}{\langle I_1\rangle_s + \langle I_o\rangle_s}\right) \tag{4}$$

$\langle I_1\rangle_d$ and $\langle I_2\rangle_d$ are the mean photocurrent values of high and low signal levels at the connection destination respectively.

$\langle I_1\rangle_s$ and $\langle I_o\rangle_s$ are the mean photocurrent values of high and low signal levels at the connection source respectively.

$$NoisePenalty = \left(\frac{\sigma_{1,s} + \sigma_{o,s}}{\sigma_{1,d} + \sigma_{0,d}}\right) \tag{5}$$

$\sigma_{1,s}$ and $\sigma_{0,s}$ are the standard deviations of high and low signal noise levels at the connection source respectively.

$\sigma_{1,d}$ and $\sigma_{0,d}$ are the standard deviations of high and low signal noise levels at the connection destination respectively. The eye-related penalty is due to the impairment effects of CD, PMD and FC, whereas the noise-related penalty is due to the impairment effects of XT, ASE, SPM, XPM and FWM. It is important to note that the variances of XT, ASE, SPM, XPM and FWM of a lightpath may be computed as the summation of the constituent electrical variances of links making up the entire lightpath.

The proposed model is comprised of three key stages. In the first phase, all the information concerned with the traffic requests and network characteristics is gathered. This information includes optical channel characteristics, network topology and capacity. The traffic characteristics incorporate data about the bitrate, lightpath demands, amongst others. Link costs are then evaluated that are based on the obtained information and characteristics. These link costs will be taken into consideration during the path selection process.

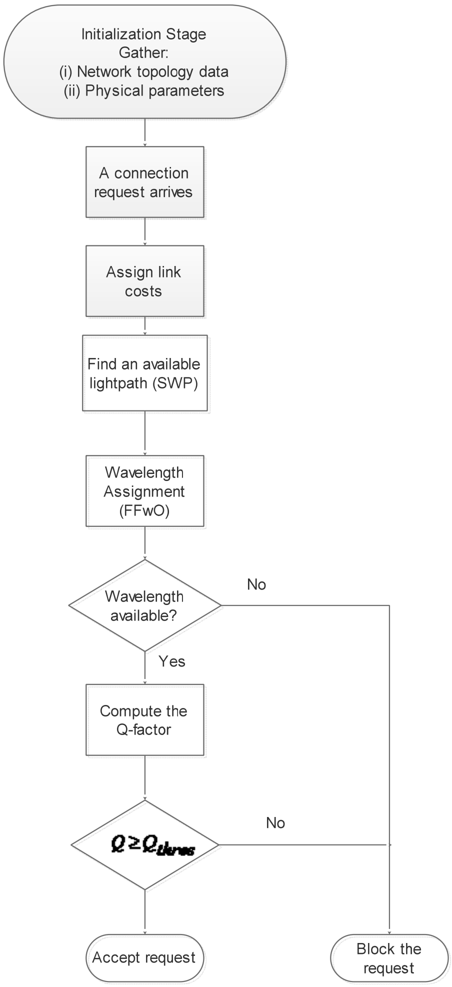

Fig. 2 Flowchart of the proposed algorithm

The second phase is responsible for the assignments of paths and wavelengths. The shortest-widest path (SWP) and first-fit with ordering (FFwO) schemes are proposed in this model. A set of *k*-shortest paths for each connection request is identified and an ILP optimization problem is solved that minimizes network costs. The final stage validates the lightpaths generated in the second stage. The analytically modeled Q-factor that incorporates the effects of physical layer impairments is employed as the link-cost metric. If a candidate lightpath meets the pre-set signal quality requirements and incorporates all the stated impairments, then a connection is established. If the proposed lightpath signal quality does not satisfy the given requirements and /or does not take into account the effects of physical impairments, the connection is blocked. Figure 2 summarizes the algorithm.

III. EVALUATION

The Pan-European Network is used in this model to verify its applicability and accuracy. The network topology has 16 nodes and 23 bidirectional fibre links. We assume that the connection requests follow a Poisson distribution and the nodes do not have wavelength conversion capabilities. Furthermore, no protection or regeneration is taken into consideration. The shortest-widest path (SWP) algorithm is employed to solve the routing sub-problem and the First-fit with Ordering (FFwO) algorithm is used to solve the wavelength assignment sub-problem.

When a connection request is received, the engine looks for the shortest-path that is least congested and process them in their order. The FFwO algorithm is then applied to choose an available wavelength from the available wavelengths (Figure 2.

Each candidate path's Q-factor is calculated and those paths that have a Q-factor that is lower than a pre-set threshold (Q_{thres}) are blocked.

We chose the whole network to consist of SSMF with a dispersion, $D = 12 \quad ps/nm/km$ an attenuation constant of $\alpha = 0.25 dB/km$ and a nonlinearity constant of $\gamma = 1.5 (W/Km)$. We also assume a communication channel plan a maximum of 40 wavelengths per link spaced at $50 \ GHz$. The threshold q-factor is configurable and overall noise figure is set at $5 \ dBw$

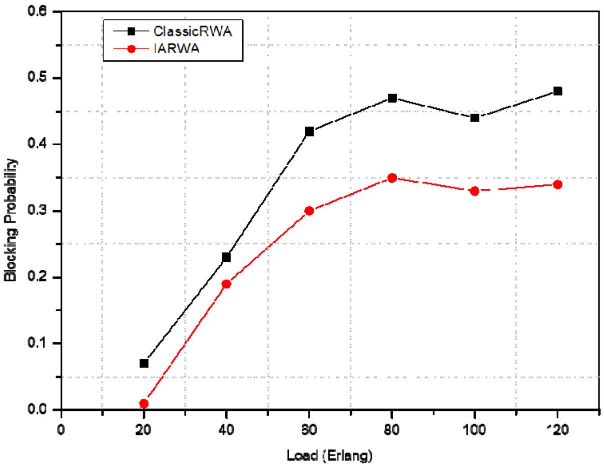

Fig. 3. The relationship between blocking probability and network load for the Pan-European Network

Figure 3 above, compares the blocking probability of the classic RWA algorithm with our proposed IA-RWA algorithm in the Pan-European Network topology. Figure 4 compares the blocking probabilities of the classic RWA algorithm with that of our proposed IA-RWA for different traffic loads in the MESHNET topology. The MESHNET topology consists of 16 mesh toroid nodes that have identical link lengths of 100 km. We can clearly observe that, at low network loads, the performances of the two algorithms is almost similar in the Pan-European Network, however, there is clear distinction of their performances at high loads. We further note that in the MESHNET topology, there is a significant reduction in the blocking probability for our proposed model compared with the Pan-European Network. This implies that the performance of the MESHNET topology is appreciably improved by our model. Furthermore, this shows that the model can certainly improve the performance of regular networks and fairly large irregular networks at high loads. In a nutshell, our proposed algorithm evidently outshines the classic one, and it thus helps improve the network performance.

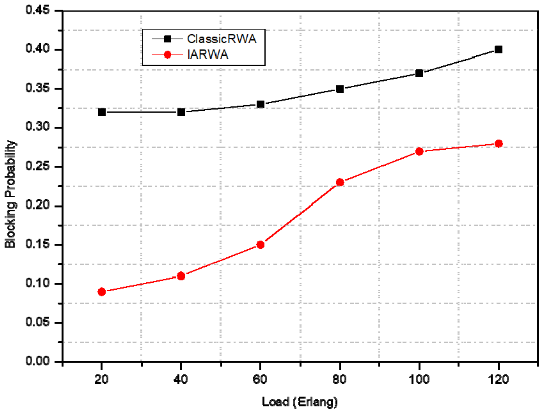

Fig. 4. Relationship between blocking probability and network load for the MESHNET topology

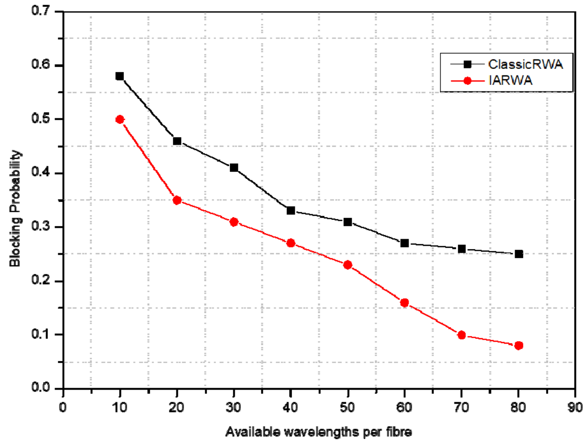

Fig. 5. Relationship between blocking probability and number of wavelengths per fibre

The simulation results of the classic RWA and our IA-RWA algorithms showing the variation of blocking probability and the number of available wavelengths per fibre are shown in Figure 5. The proposed model offers lower blocking rates, especially when the number of wavelengths is limited. When the number of wavelengths reaches a certain threshold (≈ 60), the blocking probability becomes fairly steady, implying that physical impairments become the key determinants of the network blocking rates performance. Figure 6 shows the relationship between the Q-factors and the ratio of existing lighpaths for the shortest path (SP) combined with first fit (FF) algorithm, as well as that of the SWP with FFwO algorithm. The traffic load is set at 10 Erlangs, and it can be seen that a significant ratio of the lightpaths have a Q-factor of less than 14 for the SP with FF algorithm. This is in contrast with that of the SWP, FFwO algorithm, were a substantial ratio of existing lighpaths have a Q-factor that is above 14. It is clear that SWP, FFwO algorithm leads to better utilization of network resources and satisfactory physical performance.

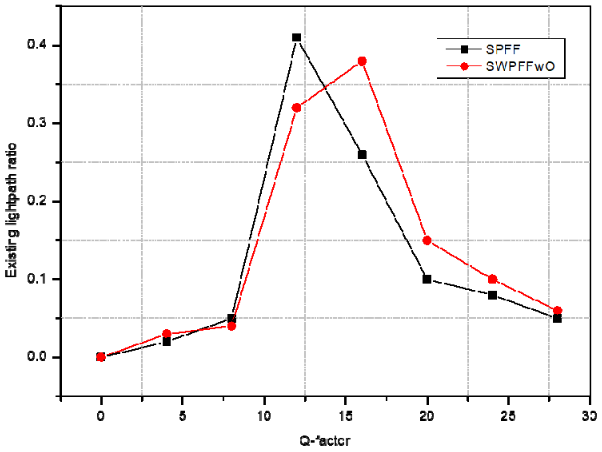

Fig. 6. Relationship between existing lightpaths and Q-factors

Figure 7 shows that the average computation time of the proposed IA-RWA algorithm is longer than that of the pure RWA algorithm. This may be due to the fact that our IA-RWA algorithm incorporates the effects of impairments in its decision-making process. In our algorithm, the set up collects information on impairment effects experienced by the signal during transmission in the selection of a route and wavelength assignment and then calculates the effects' value before finally evaluating the signal quality against a preset threshold value.

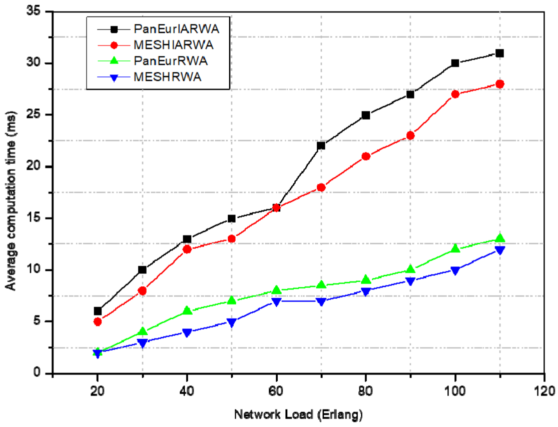

Fig. 7. Variation of average computation time with network load

This process certainly leads to an increase in computation time. It implies that a trade-off should be struck between attaining high QoT and computational time. In addition, it is also shown that classic RWA computational time is more or less the same regardless of the network topology, especially at low network loads.

IV. CONCLUSION

In this paper, a Q-factor tool that incorporates most of the pertinent physical layer impairments is proposed. The tool is evaluated through simulations, and a comparison of its performance with those of traditional approaches is made. The proposed Q-factor tool outperforms the ones that are traditionally employed. An analytical technique to compute the blocking probabilities for RWA with physical impairments in transparent optical transport networks is also proposed. Numerical examples are also provided to show the performance of the proposed model, and it is validated through the use of simulations. QoT-aware and QoT-guaranteed RWA approaches are implemented in various networks to evaluate the performance of the model, and its validation is done through simulations. It is clearly observed that the proposed model provides reasonably accurate results in all given network scenarios.

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